Electromagnetic Probes from a Hydrodynamical Model with Shear and Bulk Viscosities

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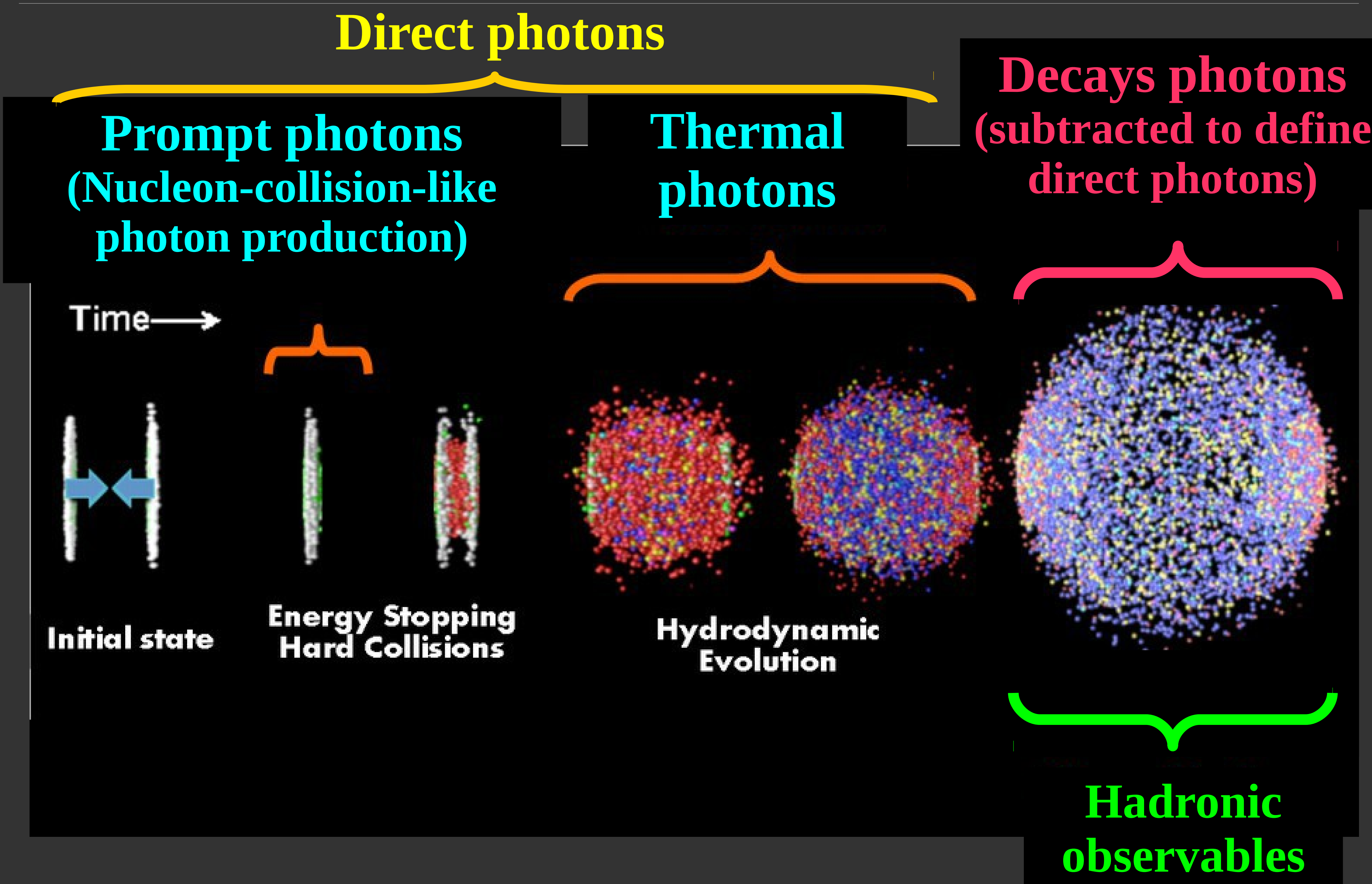
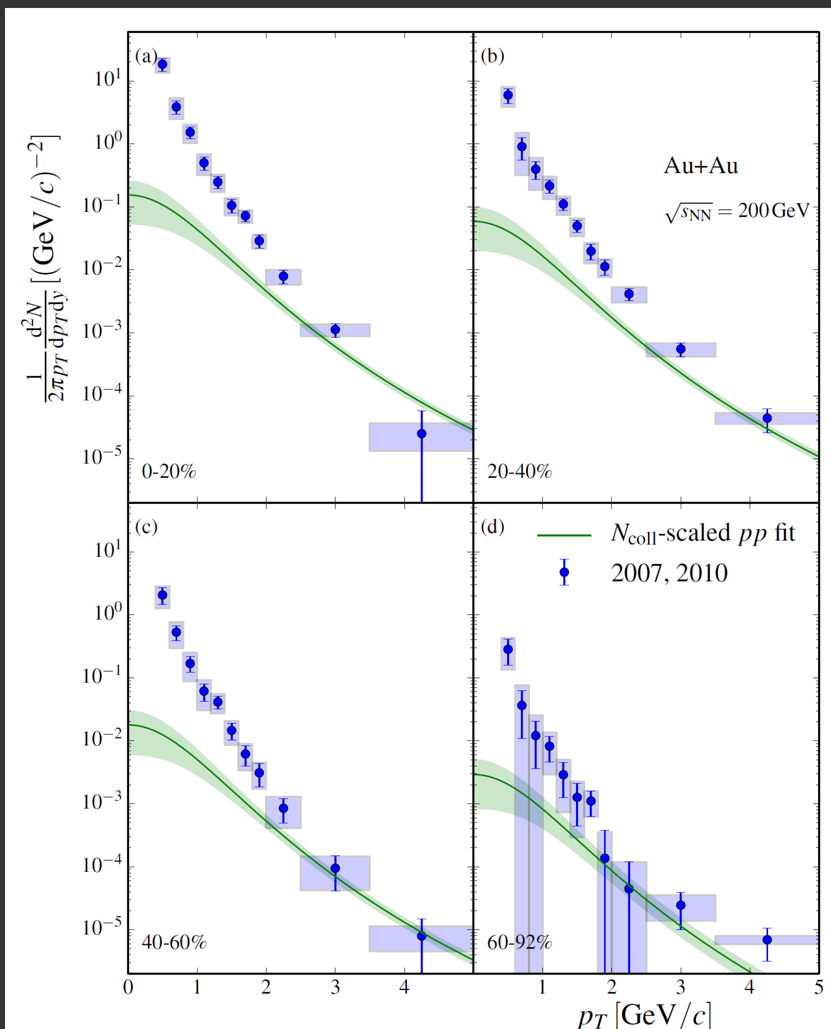
2015 RHIC & AGS Annual Users' Meeting

June 9, 2015

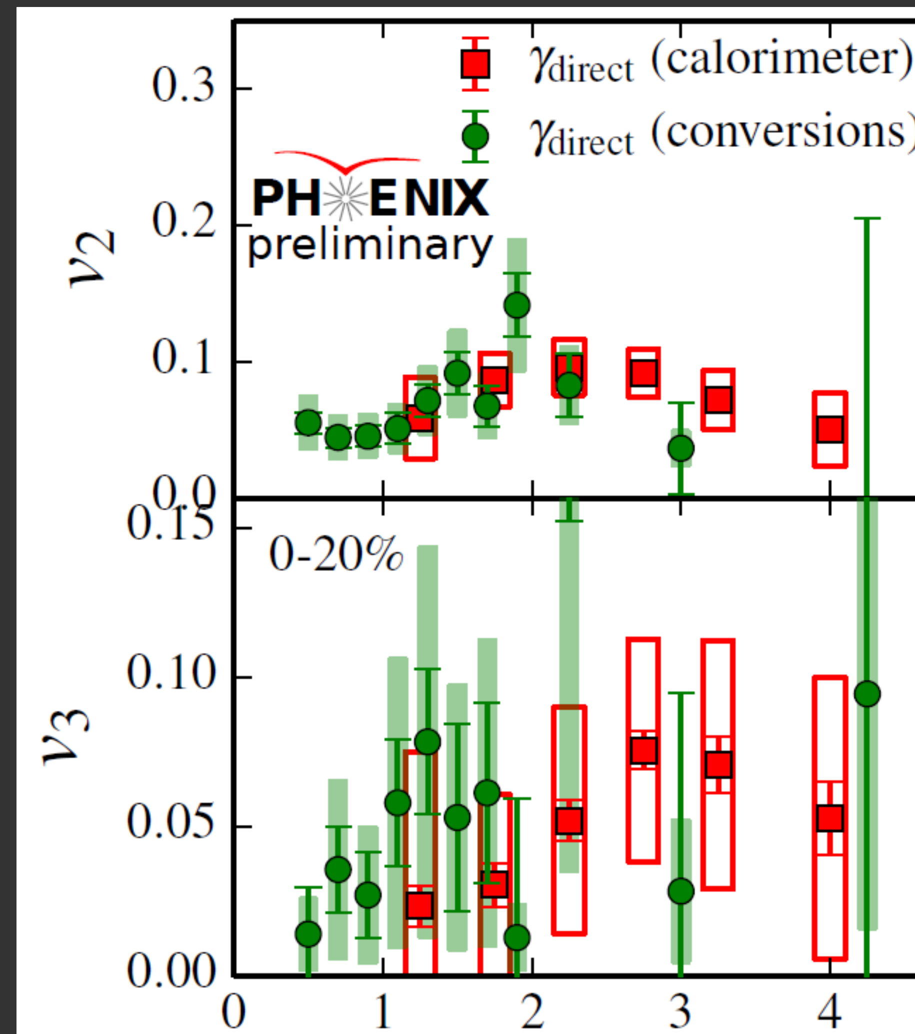
Photon and hadron sources in HIC



Direct photon puzzle: anisotropy & spectra



Direct photon spectra

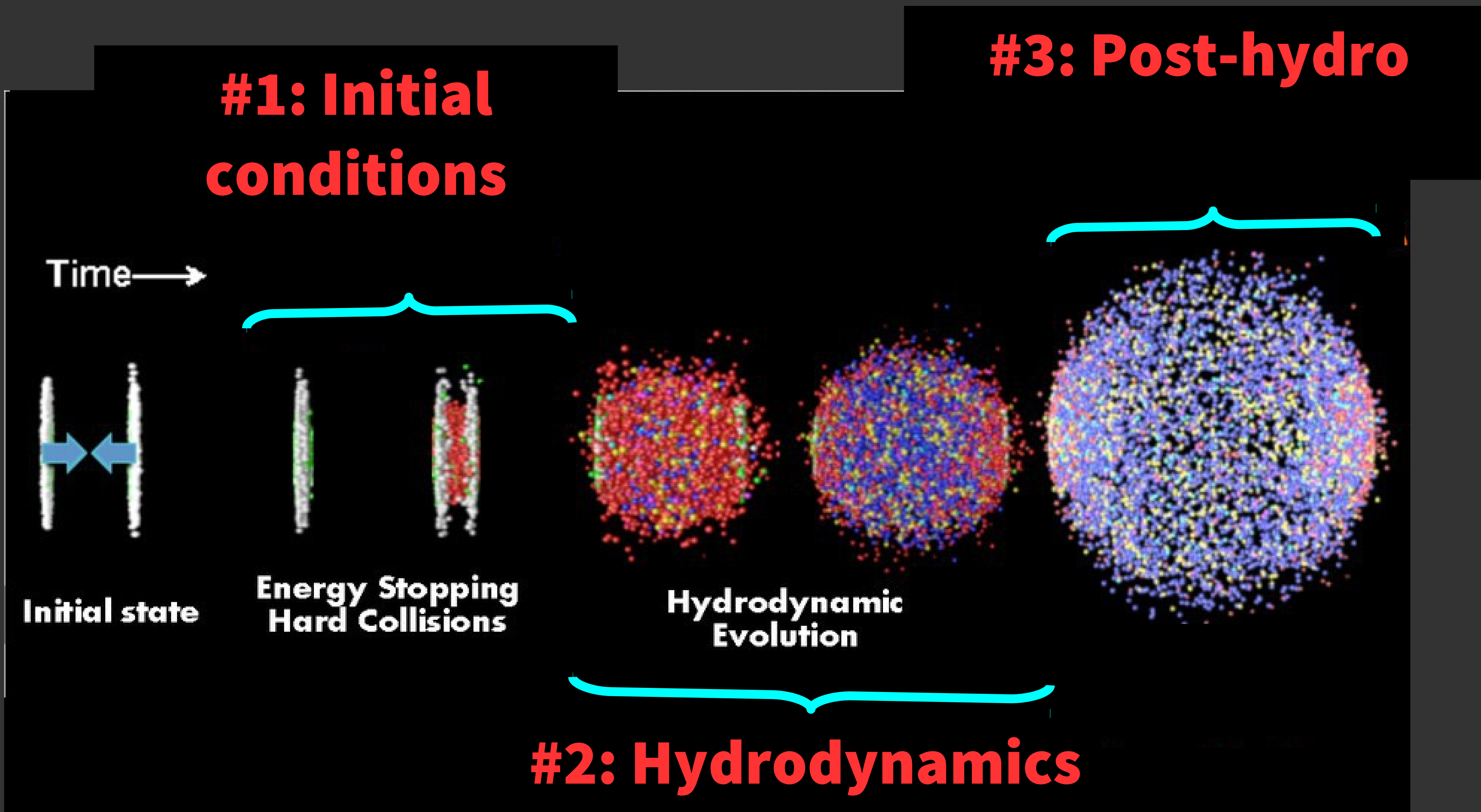


Direct photon v_2/v_3

Outline

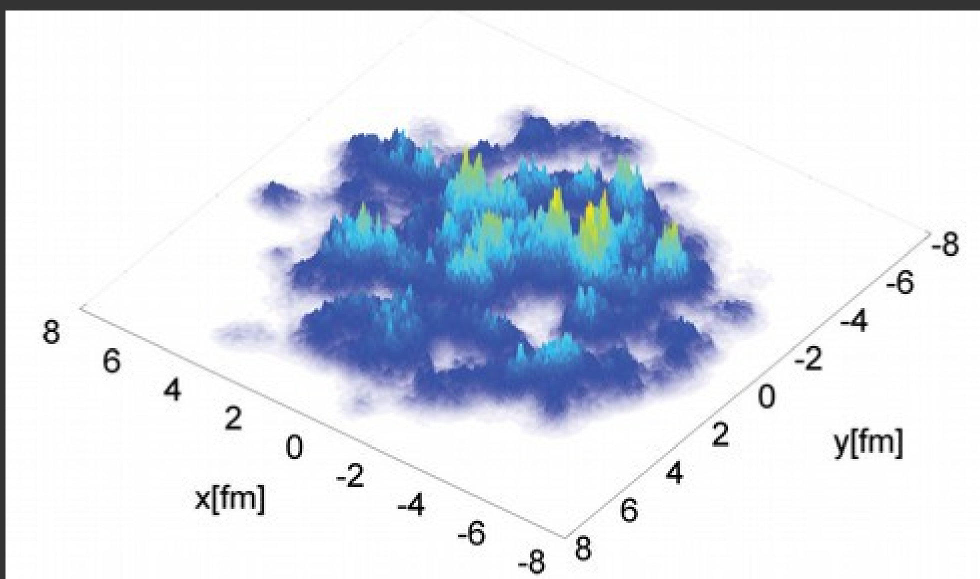
- Hydrodynamical model & hadrons
- Photons and bulk viscosity
  - Comparison with data
  - Understanding the effect of bulk viscosity
  - Other changes
- Summary & outlook

Hydrodynamical model



Initial conditions

- Event-by-event IP-Glasma (**τ<0.4 fm/c**)



CGC/IP-Sat initial conditions w/ classical Yang-Mills evolution

Energy density (slightly renormalised) and transverse flow

(Schenke, Tribedy, Venugopalan. 2012)

Second order hydrodynamics

- Hydrodynamics - MUSIC (**τ>0.4 fm/c**)

2+1D second-order (viscous) relativistic hydrodynamics

$$\partial_\mu T^{\mu\nu}(X) = 0$$

$$T^{\mu\nu}(X) = \epsilon(X) u^\mu(X) u^\nu(X) - [\mathcal{P}(X) + \boxed{\Pi(X)}]\, \Delta^{\mu\nu}(X) + \pi^{\mu\nu}(X)$$

Bulk pressure

Shear stress tensor

Equation of motion for the bulk pressure

$$\boxed{\tau_\Pi \dot{\Pi} + \Pi = -\zeta\theta - \delta_{\Pi\Pi}\Pi\theta + \lambda_{\Pi\pi}\pi^{\mu\nu}\sigma_{\mu\nu}}$$

(Denicol et al. 2012)

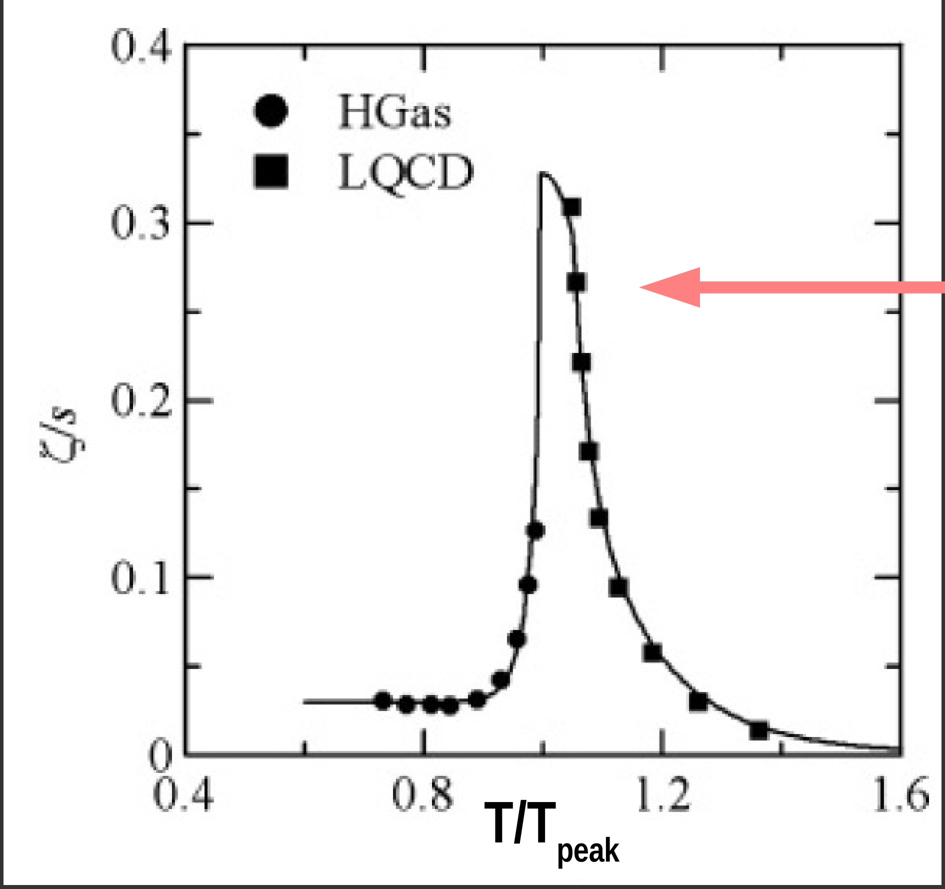
$$\tau_\pi \Delta^{\mu\nu}_{\alpha\beta}\dot{\pi}^{\alpha\beta} + \pi^{\mu\nu} = 2\eta\sigma^{\mu\nu} - \delta_{\pi\pi}\pi^{\mu\nu}\theta - \tau_{\pi\pi}\Delta^{\mu\nu}_{\alpha\beta}\pi^{\lambda\alpha}\sigma^\beta_\lambda + \lambda_{\pi\Pi}\Pi\sigma^{\mu\nu} + \varphi_7\Delta^{\mu\nu}_{\alpha\beta}\pi^{\lambda\alpha}\pi^\beta_\lambda$$

Equation of motion for the shear tensor

Bulk viscosity

High temperature QGP: ζ~0

Cross-over and low temperature: ζ~?



Use this parametrization in this work (peak at 180 MeV)

Inspired by:

HRG: Noronha-Hostler, Noronha and Greiner. 2009

(Lattice: Karsch, Kharzeev and Tuchin. 2008)

(from Denicol, Kodama, Koide, Mota. 2009)

Shear viscosity

- Hydrodynamics - MUSIC (**τ>0.4 fm/c**)

2+1D second-order (viscous) relativistic hydrodynamics

Shear viscosity $\eta/s = constant$ $\left\{ \textbf{RHIC: 0.08 / LHC: 0.095} \right\}$

$$\tau_\Pi \dot{\Pi} + \Pi = -\zeta\theta - \delta_{\Pi\Pi}\Pi\theta + \lambda_{\Pi\pi}\pi^{\mu\nu}\sigma_{\mu\nu}$$

$$\tau_\pi \Delta^{\mu\nu}_{\alpha\beta}\pi^{\alpha\beta} + \pi^{\mu\nu} = 2\boxed{\eta}\sigma^{\mu\nu} - \delta_{\pi\pi}\pi^{\mu\nu}\theta - \tau_{\pi\pi}\Delta^{\mu\nu}_{\alpha\beta}\pi^{\lambda\alpha}\sigma^{\beta}_{\lambda} + \lambda_{\pi\Pi}\Pi\sigma^{\mu\nu} + \varphi_7\Delta^{\mu\nu}_{\alpha\beta}\pi^{\lambda\alpha}\pi^{\beta}_{\lambda}$$

Second order transport coefficients

- Hydrodynamics - MUSIC (**τ>0.4 fm/c**)

2+1D second-order (viscous) relativistic hydrodynamics

$$\boxed{\tau_\Pi}\dot{\Pi} + \Pi = -\zeta\theta - \boxed{\delta_{\Pi\Pi}}\Pi\theta + \boxed{\lambda_{\Pi\pi}}\pi^{\mu\nu}\sigma_{\mu\nu}$$

$$\boxed{\tau_\pi}\Delta^{\mu\nu}_{\alpha\beta}\pi^{\alpha\beta} + \pi^{\mu\nu} = 2\eta\sigma^{\mu\nu} - \boxed{\delta_{\pi\pi}}\pi^{\mu\nu}\theta - \boxed{\tau_{\pi\pi}}\Delta^{\mu\nu}_{\alpha\beta}\pi^{\lambda\alpha}\sigma^{\beta}_{\lambda} + \boxed{\lambda_{\pi\Pi}}\Pi\sigma^{\mu\nu} + \boxed{\varphi_7}\Delta^{\mu\nu}_{\alpha\beta}\pi^{\lambda\alpha}\pi^{\beta}_{\lambda}$$

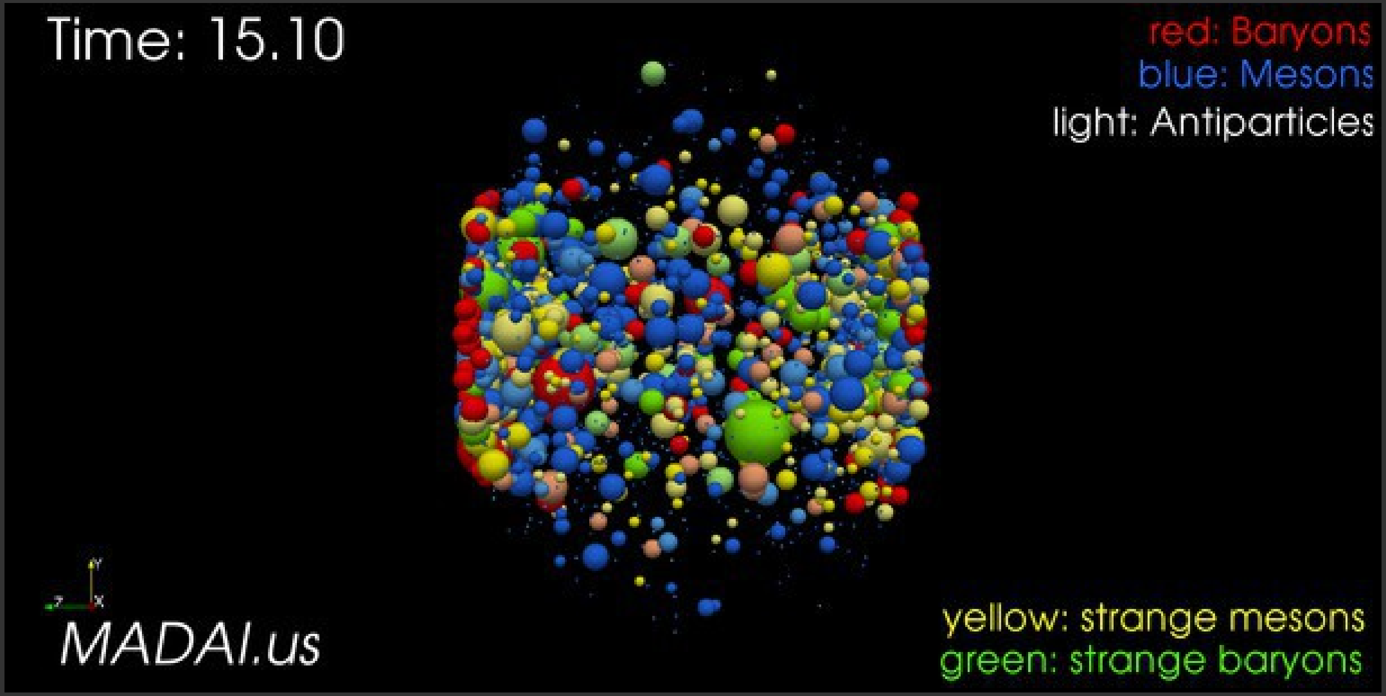
2^{nd} order transport coefficients:
related to 1^{st} order ones with kinetic theory
e.g.

$$\tau_\Pi = \frac{\zeta}{15\left(\frac{1}{3} - c_s^2\right)^2(\epsilon + \mathcal{P})}$$

(Molnar, Niemi, Denicol, and Rischke. 2014; Denicol, Jeon and Gale. 2014)

After hydro: afterburner

- UrQMD (τ>0.4 fm/c & **$T<T_{sw}$**)



At the RHIC:

T_{sw}=165 MeV

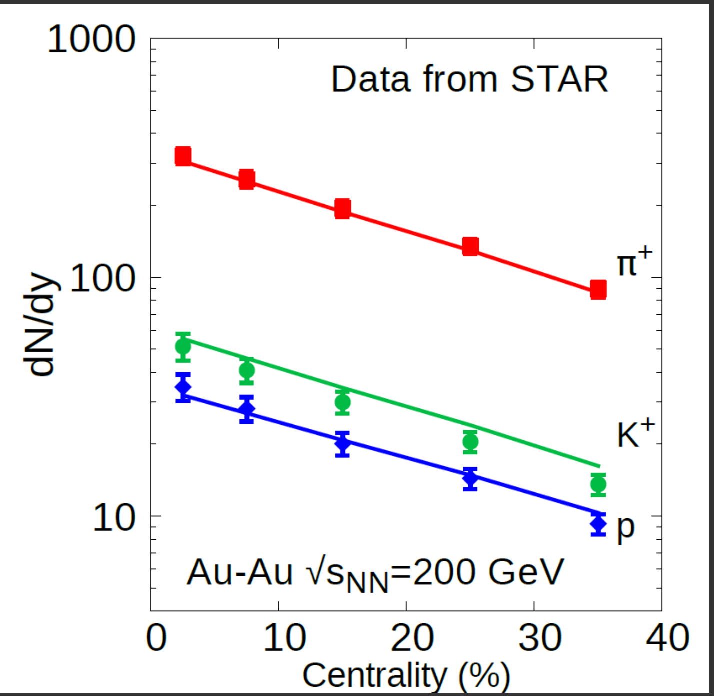
At the LHC:

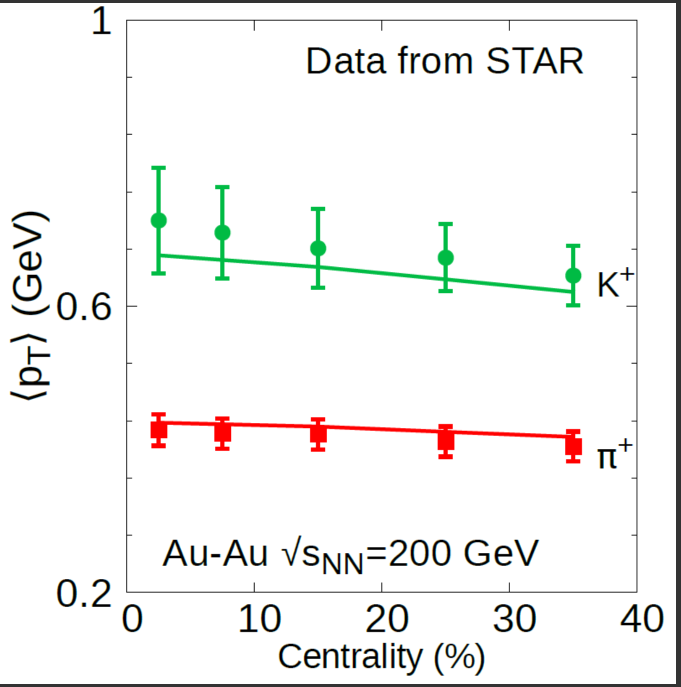
T_{sw}=145 MeV

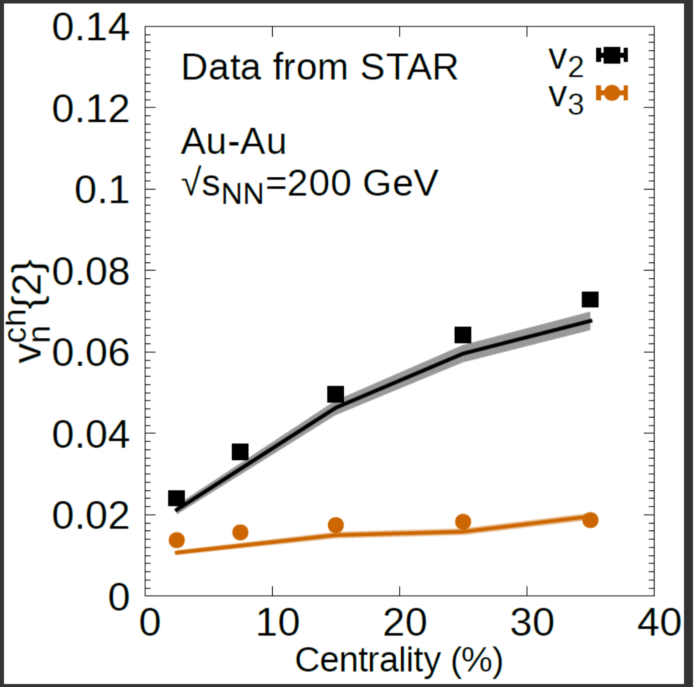
Hydrodynamical model

Comparison with hadronic data

RHIC $\sqrt{s_{NN}}$=200 GeV







Multiplicity of pions, kaons and protons

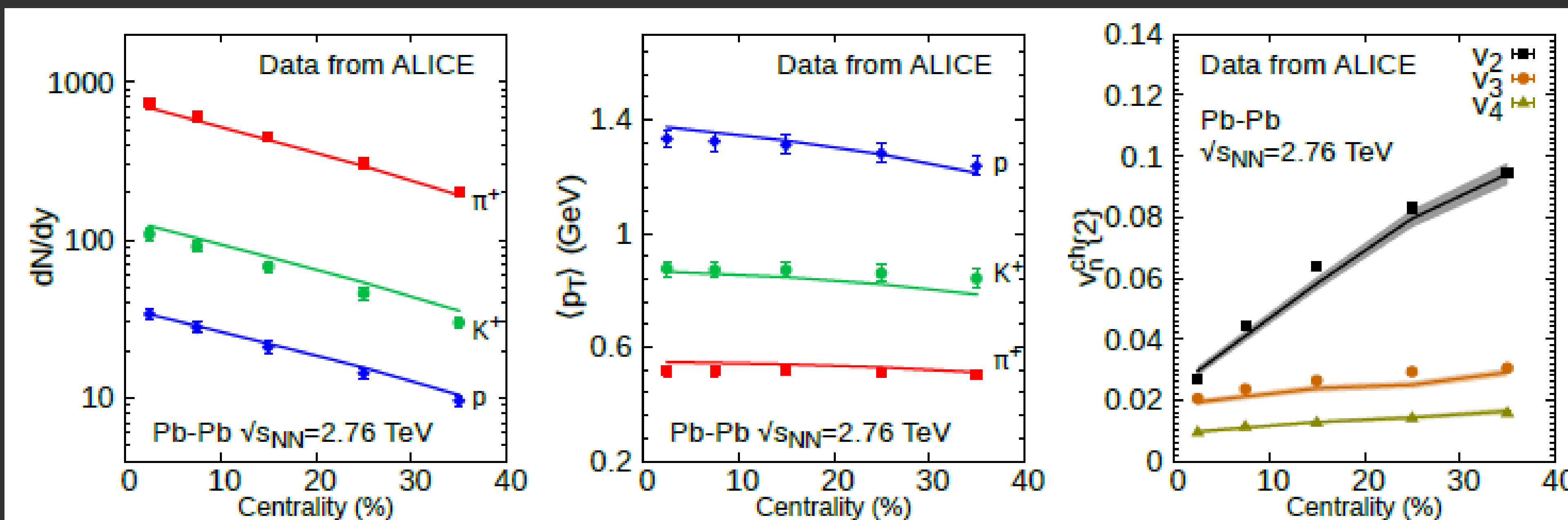
Mean transverse momentum of pions and kaons

v_2 and v_3 of charged hadrons

Hadronic observables?

Well described by hydrodynamical model at the RHIC

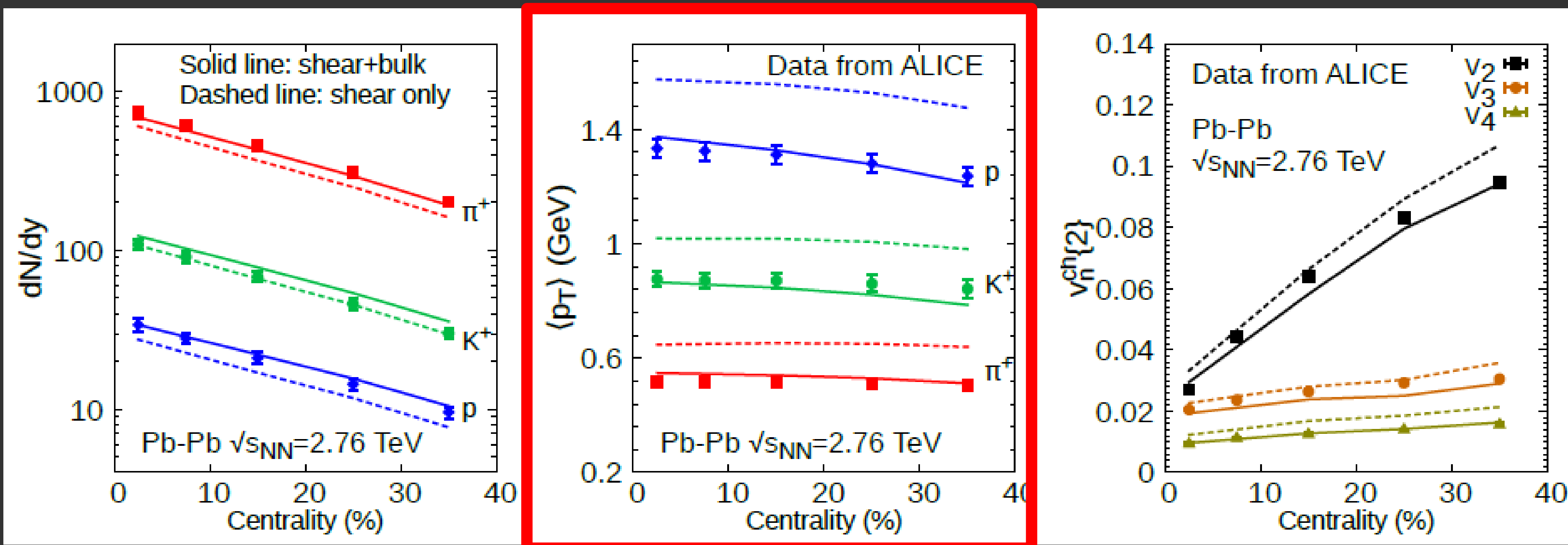
Similar agreement found at the LHC (see arXiv:1502.01675)



Bulk viscosity & hadrons?

Bulk viscosity important for average transverse momentum

Solid line: w/ bulk viscosity
Dashed line: w/o bulk viscosity (shear only)



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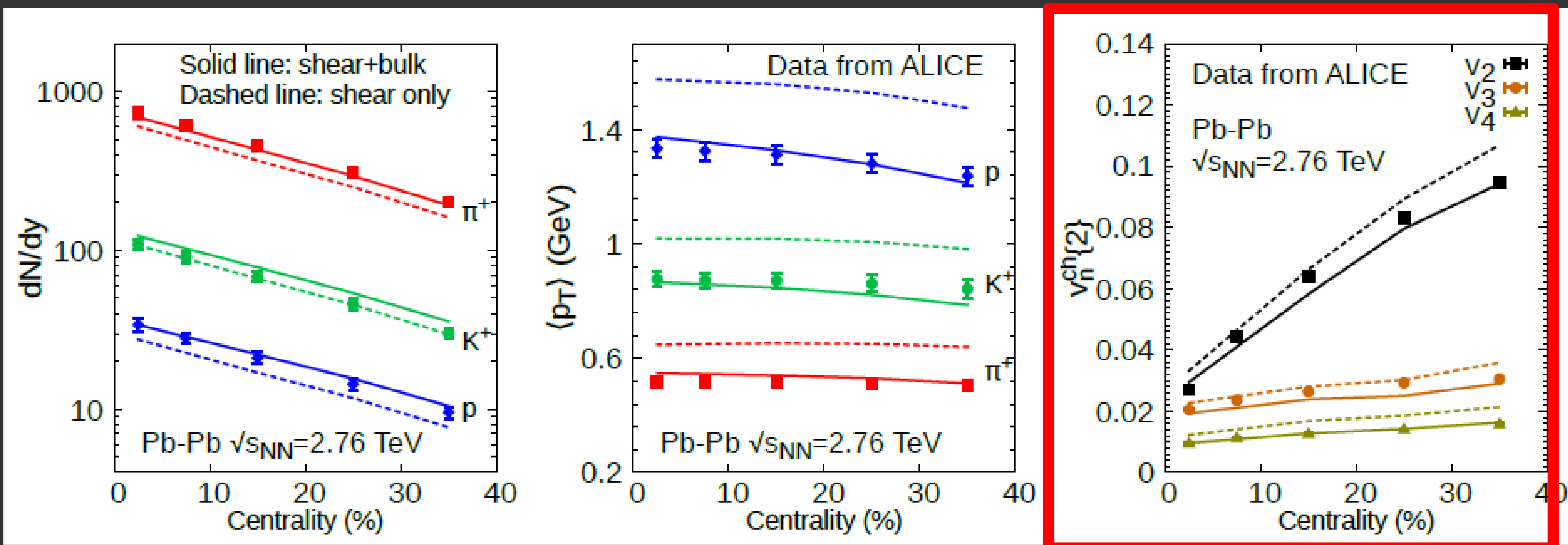


Also: changed best η/s from ~0.2 to ~0.1

Direct photons

How are they computed?

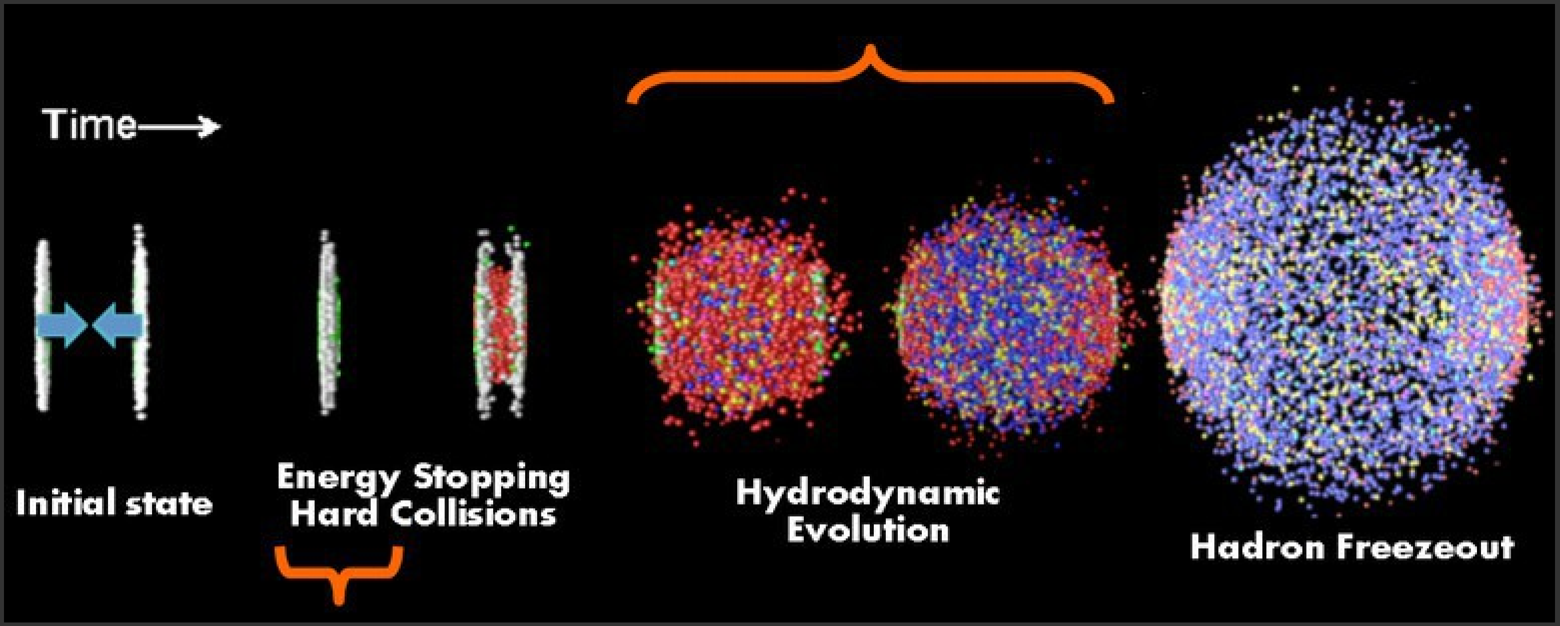
Photon production

Thermal photons:

$$E\frac{d^3N}{d\mathbf{k}} = \int d^4X \boxed{E\frac{d^3\Gamma}{d\mathbf{k}}}\left(K^\mu, \boxed{u^\mu(X), T(X), \pi^{\mu\nu}(X), \Pi(X)}\right)$$

“Thermal” photon production rate

Spacetime profile of medium



Prompt photons: NLO perturbative QCD + nuclear p.d.f.'s + isospin effect, scaled by the number of binary collisions

Thermal photon emission rate

$$E\frac{d^3N}{d\mathbf{k}} = \int d^4X\, E\frac{d^3\Gamma}{d\mathbf{k}}(K^\mu, u^\mu(X), T(X), \pi^{\mu\nu}(X), \Pi(X))$$

- Photon production rate

less hot (hadron gas) Temperature very hot (QGP)

Effective Lagrangian

(Switch at 180 MeV)

Perturbative expansion in α_s

- Mesons (Turbide, Gale, Rapp. 2004)
- Baryons (Rapp et al)
- $\pi\pi$ bremsstrahlung (Rapp et al)

Include corrections due to viscosity

Compton scattering
+ quark-antiquark annihilation
+bremsstrahlung (Arnold, Moore, Yaffe. 2002)

Thermal photon emission rate

$$E\frac{d^3N}{d\mathbf{k}} = \int d^4X\, E\frac{d^3\Gamma}{d\mathbf{k}}(K^\mu, u^\mu(X), T(X), \pi^{\mu\nu}(X), \Pi(X))$$

- Photon production rate

less hot (hadron gas) — Temperature — *very hot (QGP)*

Effective Lagrangian

- Mesons (Turbide, Gale, Rapp. 2004)
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(Switch at 180 MeV)

Include corrections due to viscosity

Perturbative expansion in α_s

Compton scattering
+ quark-antiquark annihilation
+bremsstrahlung (Arnold, Moore, Yaffe. 2002)

Not included in our previous calculations

Thermal rates: uncertainties

What is the photon emission rate of QCD matter in heavy ion collisions?

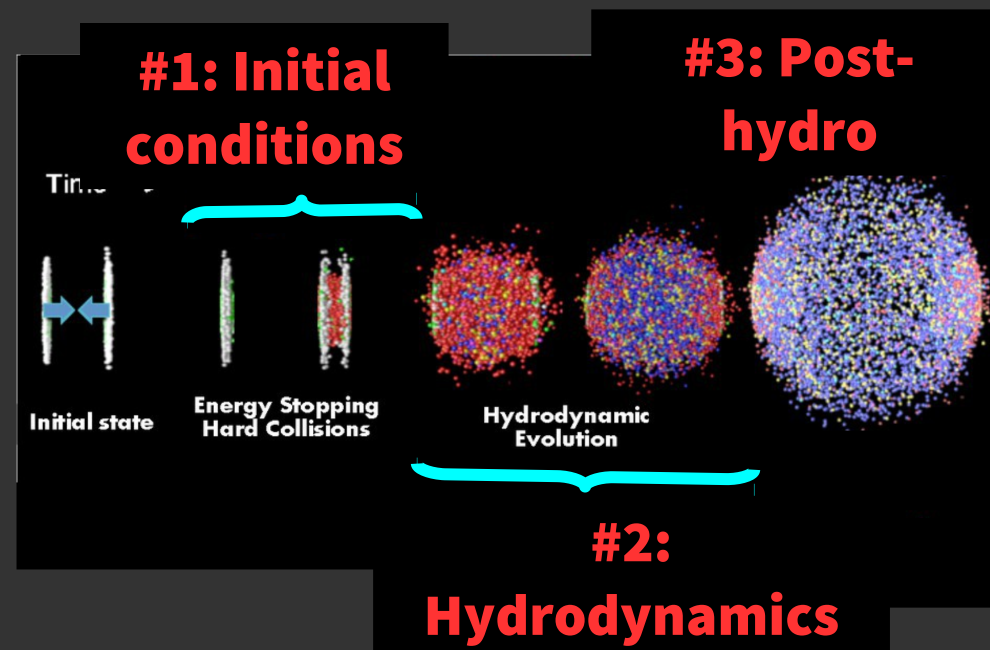
- High temperature:
  - Perturbative QGP (Arnold, Moore & Yaffe)
  - Semi-QGP (arXiv:1409.4778,1504.01770) [c.f. Shu Lin's talk]
  - Tsallis tails (McLerran & Schenke)
  - Many other investigations [see Akihiko Monnai's talk]
- Low temperature:
  - Effective Lagrangian, ρ spectral function, ... (McGill/Texas A&M)
  - Chiral reduction & density expansion (Dusling & Zahed)

Post-hydro photons

Photons after hydro phase?

Hadrons:
UrQMD

Photons:
Not yet calculated from transport model



▶ **Run hydro to lower temperature (105 MeV) instead**

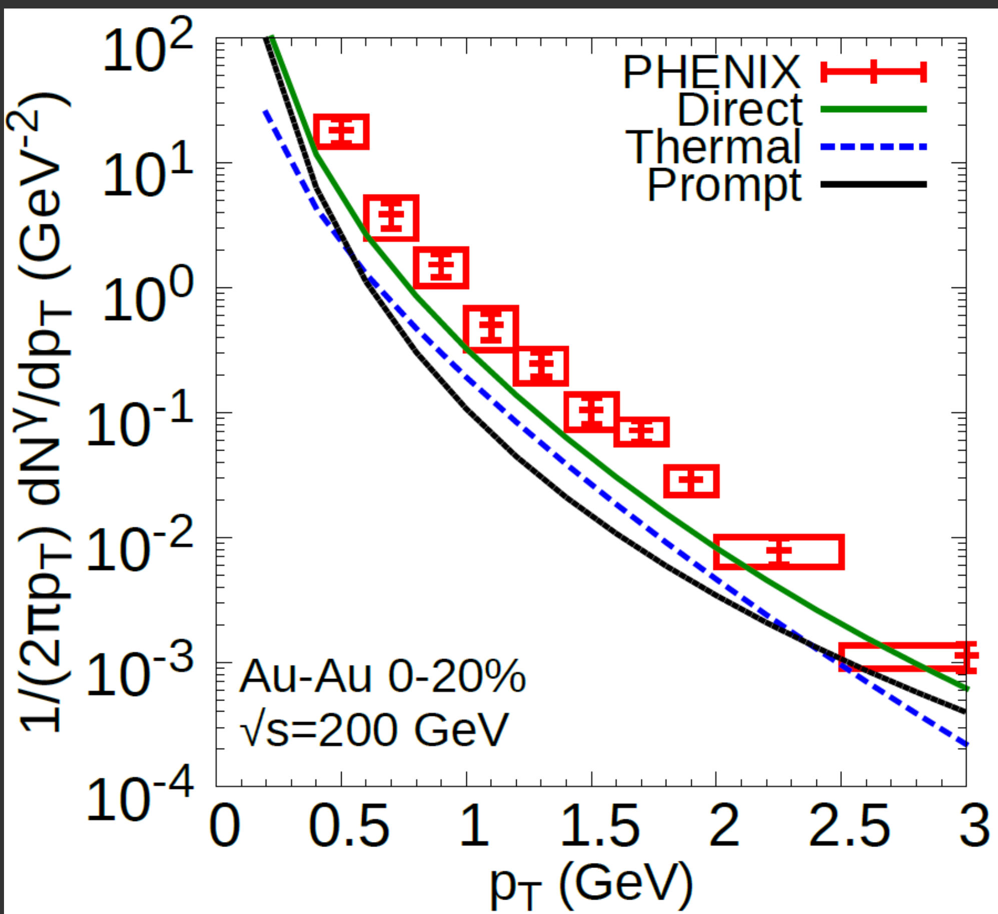
Coarse-grained UrQMD vs hydro: Huovinen, Belkacem, Ellis and Kapusta. 2002

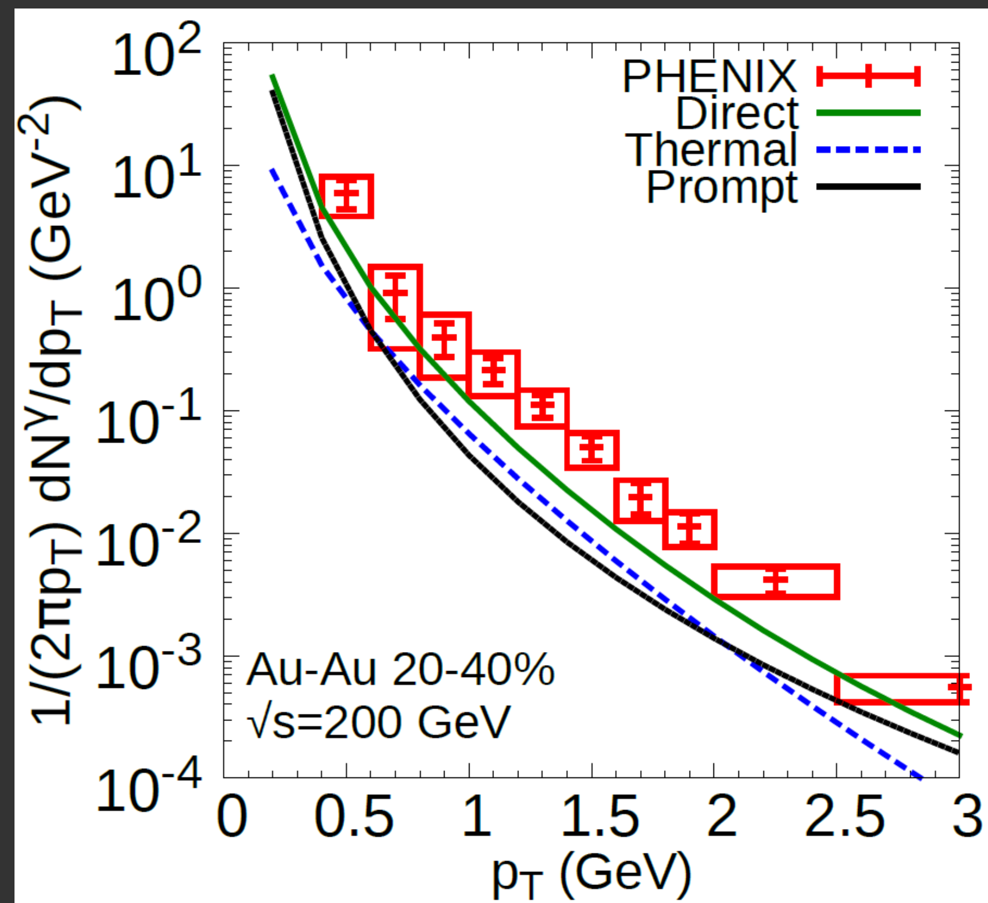
Direct photons

Comparison with data

RHIC $\sqrt{s_{NN}}$=200 GeV: spectra

Direct photon spectra





0-20% **RHIC** **20-40%**

Evaluating v_n

PHENIX and ALICE measure this in small centrality bins

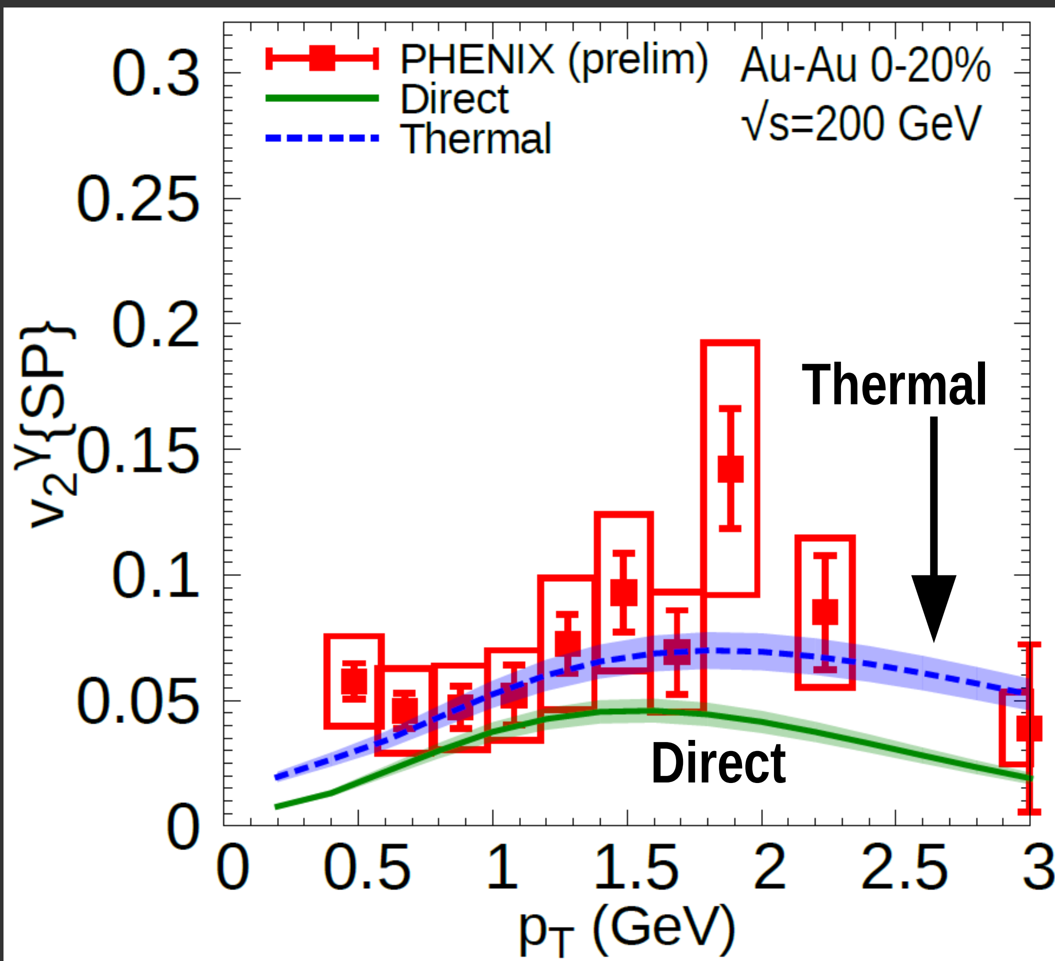
$$v_n^{\gamma}\{EP\} \simeq \frac{\langle v_n^{\gamma} v_n^{h} \cos[n(\Psi_n^{\gamma} - \Psi_n^{h})]\rangle}{\sqrt{\langle (v_n^{h})^2 \rangle}}$$

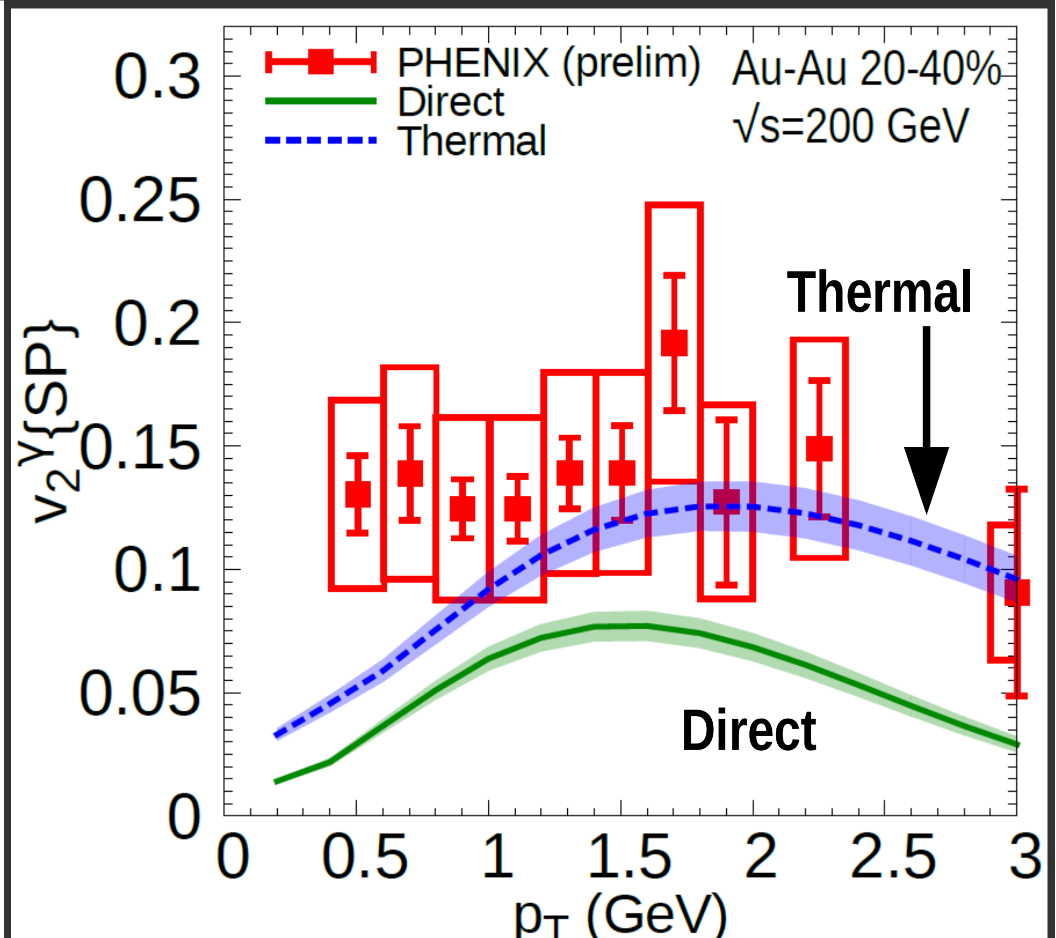
and recombine into larger bins:

$$v_n([c_{min}, c_{max}]) = \frac{\sum_{c\in[c_{min},c_{max}]} v_n^c N_{\gamma}^c}{\sum_{c\in[c_{min},c_{max}]} N_{\gamma}^c}$$

RHIC $\sqrt{s}_{NN}$=200 GeV: v_2

Direct photon v_2





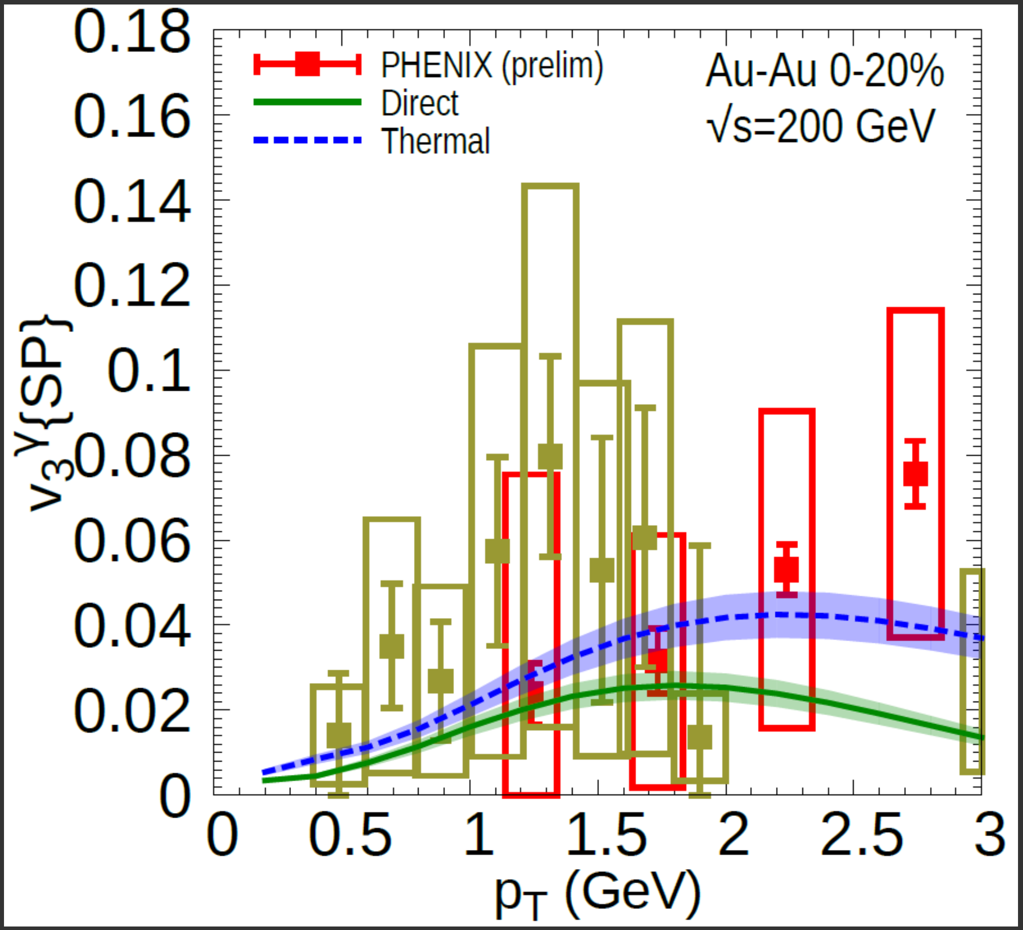
0-20%

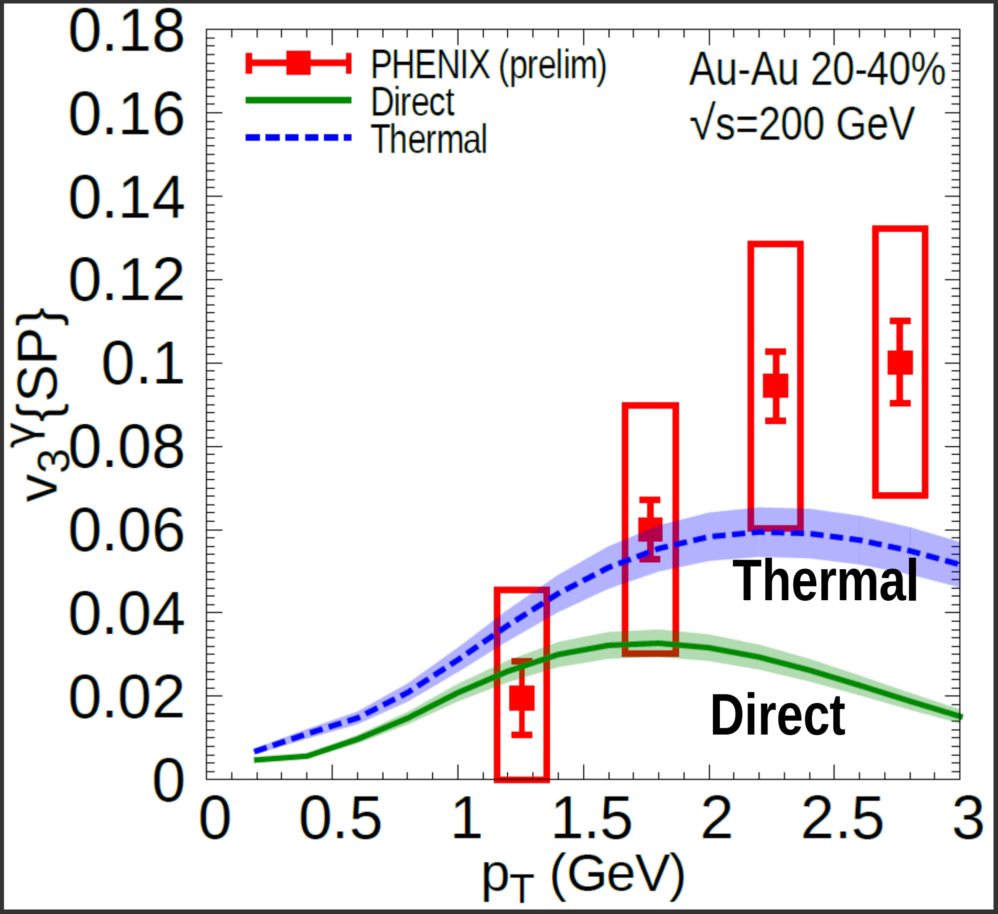
20-40%

RHIC

RHIC $\sqrt{s_{NN}}$=200 GeV: v_3

Direct photon v_3

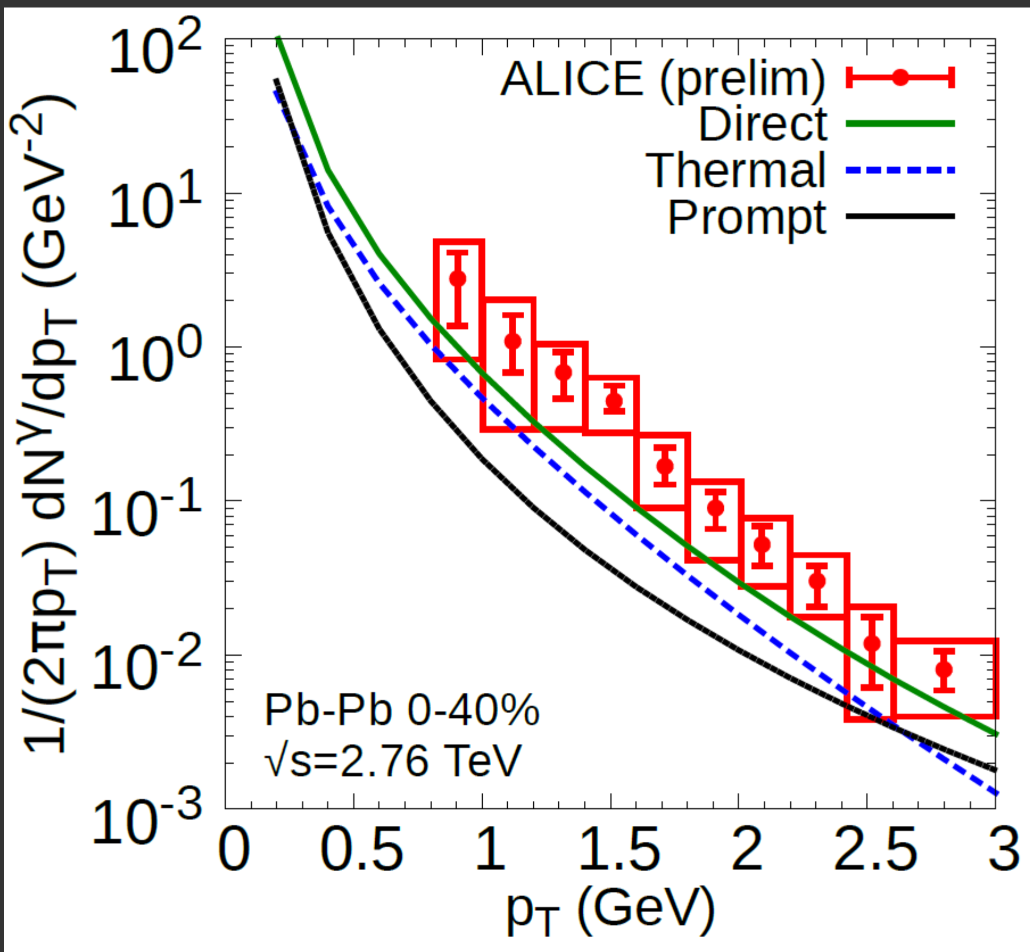




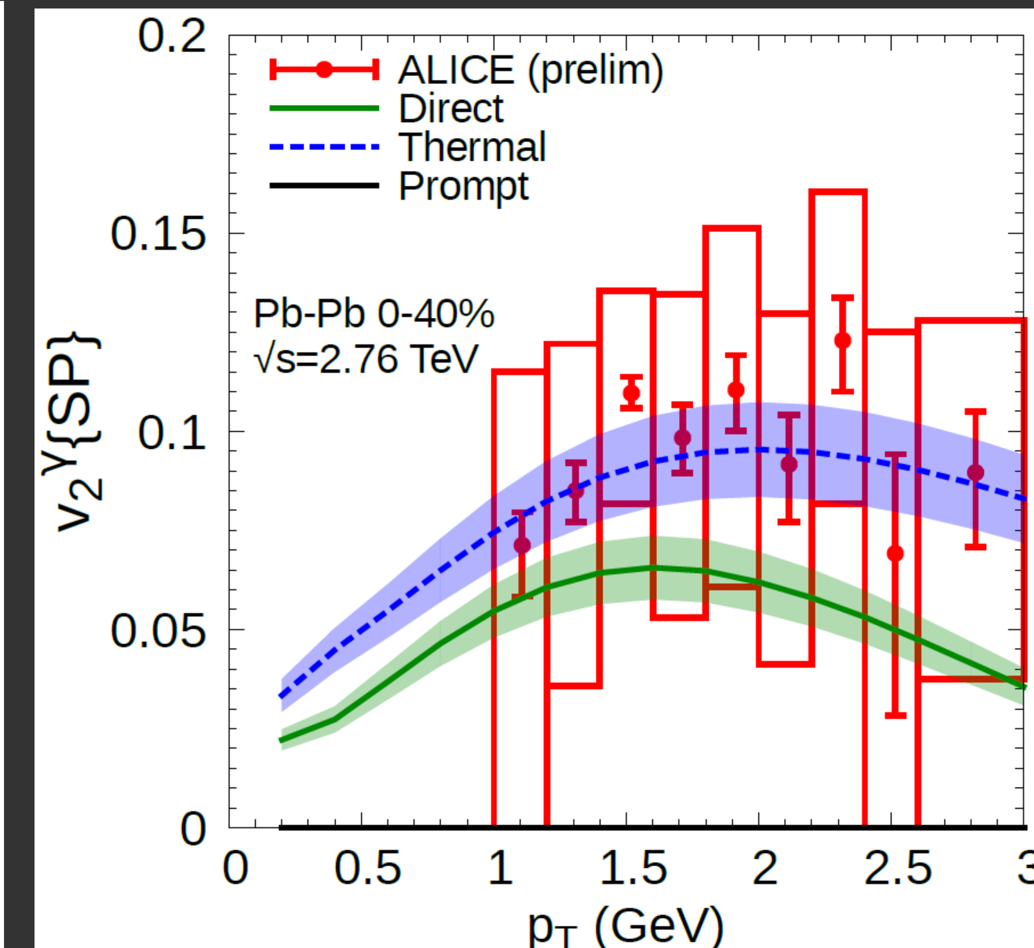
0-20% **RHIC** **20-40%**

LHC $\sqrt{s}_{NN}$=2760 GeV

Direct photon spectra



Direct photon v_2



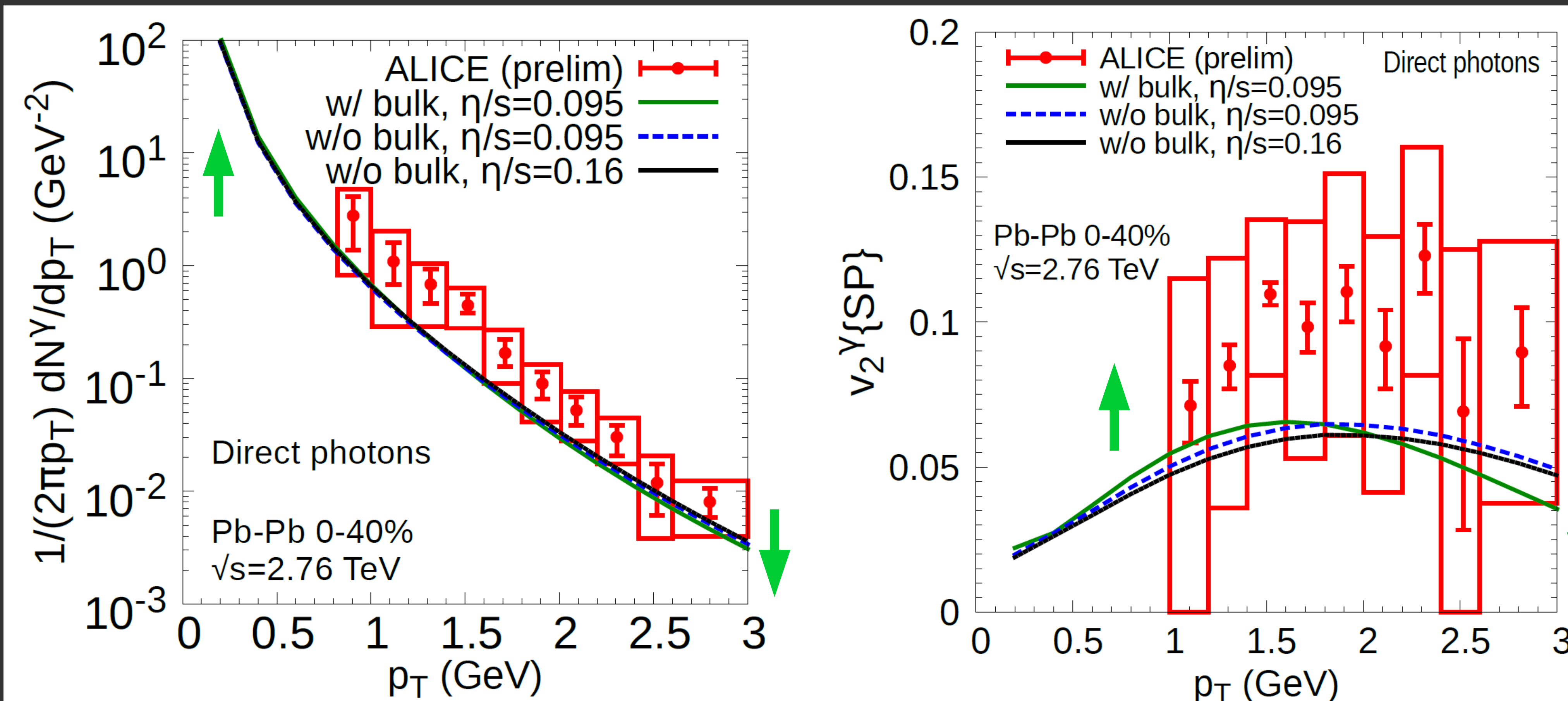
LHC 0-40%

Direct photons

Effect of bulk viscosity

(Shown for LHC calculations)

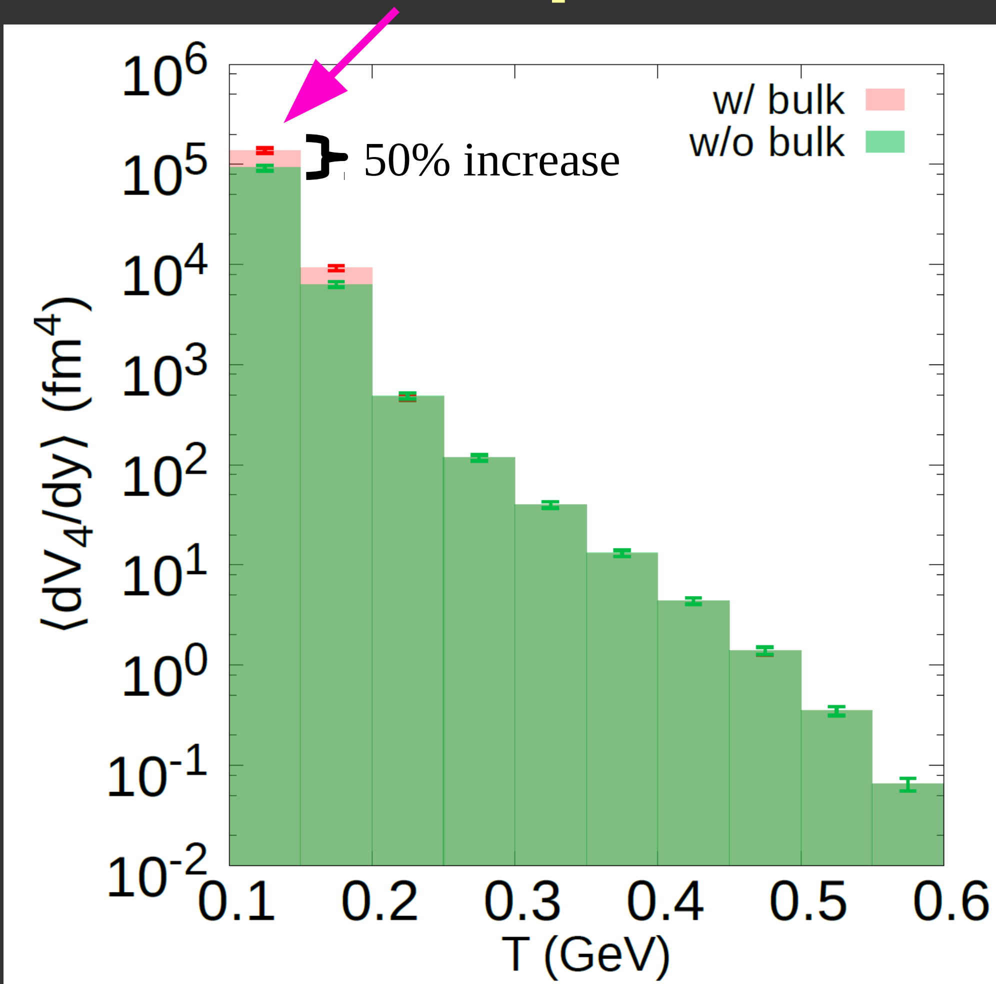
Bulk: change shape of v_2



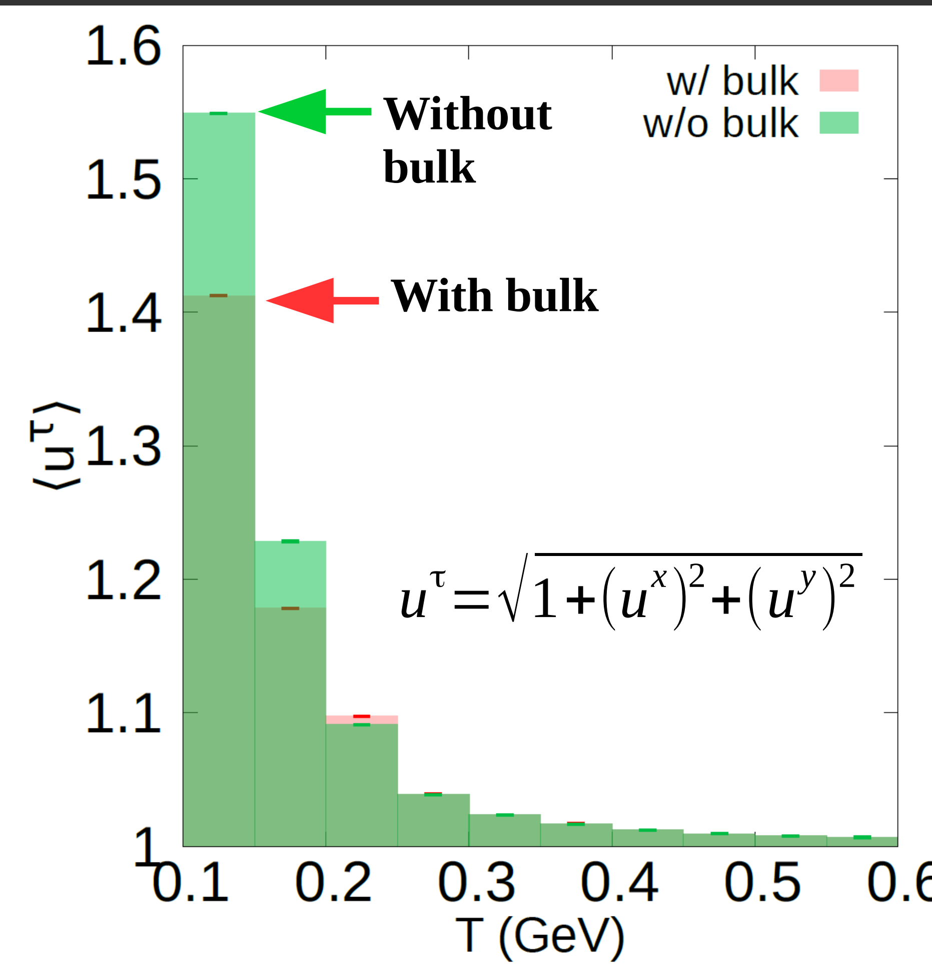
LHC 0-40%

Spacetime and flow profiles

Increased spacetime volume at low temperature



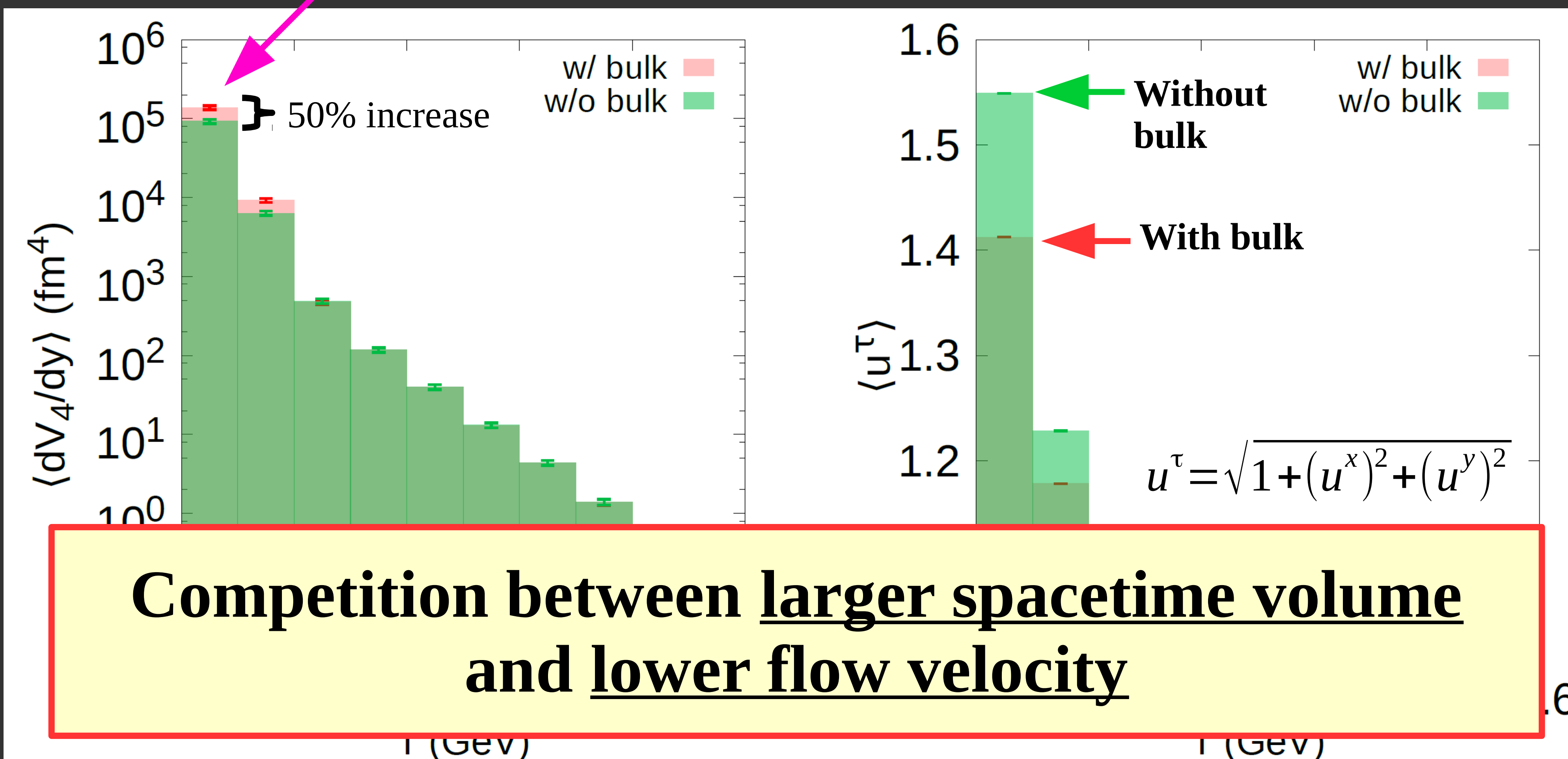
Decreased flow velocity at low temperature



Spacetime and flow profiles

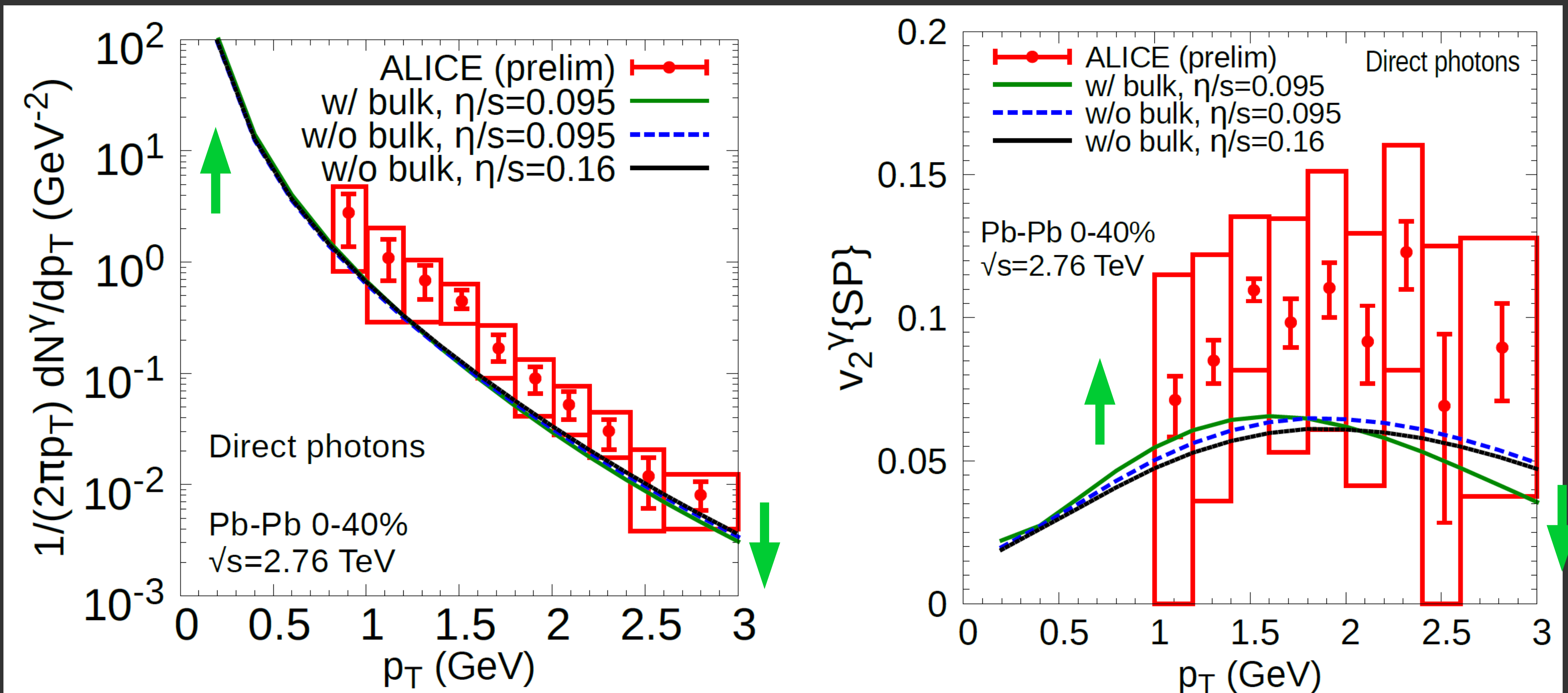
Increased spacetime volume at low temperature

Decreased flow velocity at low temperature



Competition between <u>larger spacetime volume</u> and <u>lower flow velocity</u>

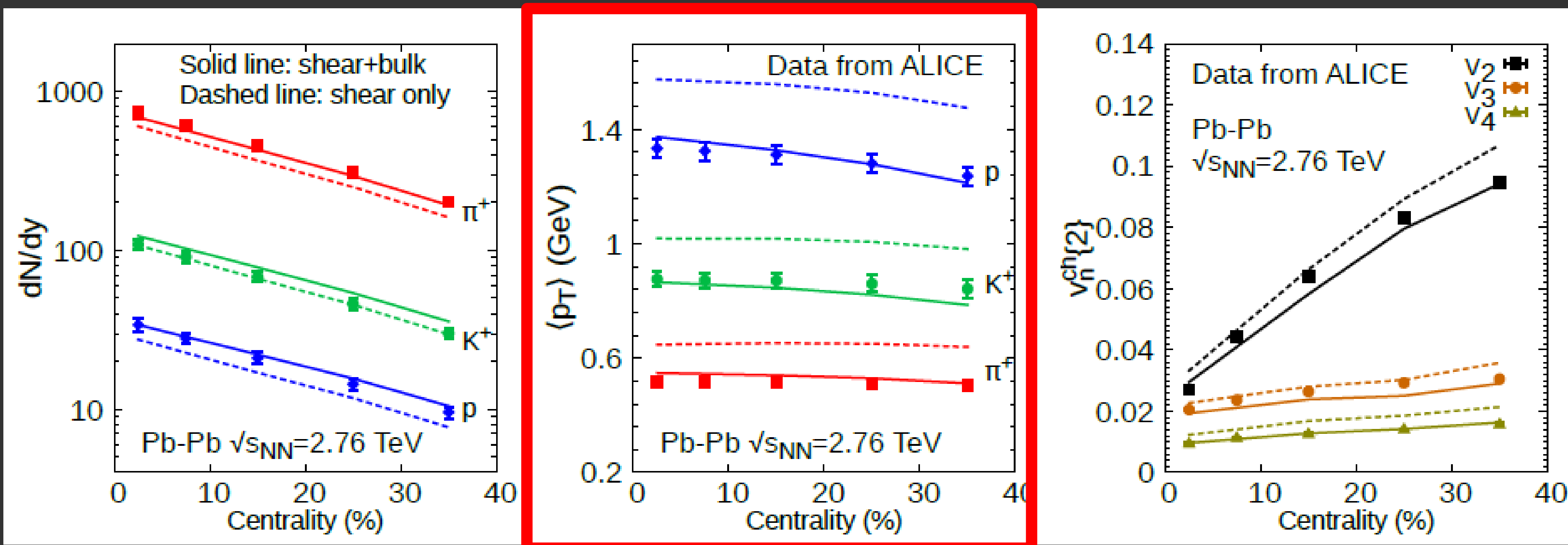
Bulk: change shape of v_2



LHC 0-40%

Indirect effect of bulk viscosity & other changes

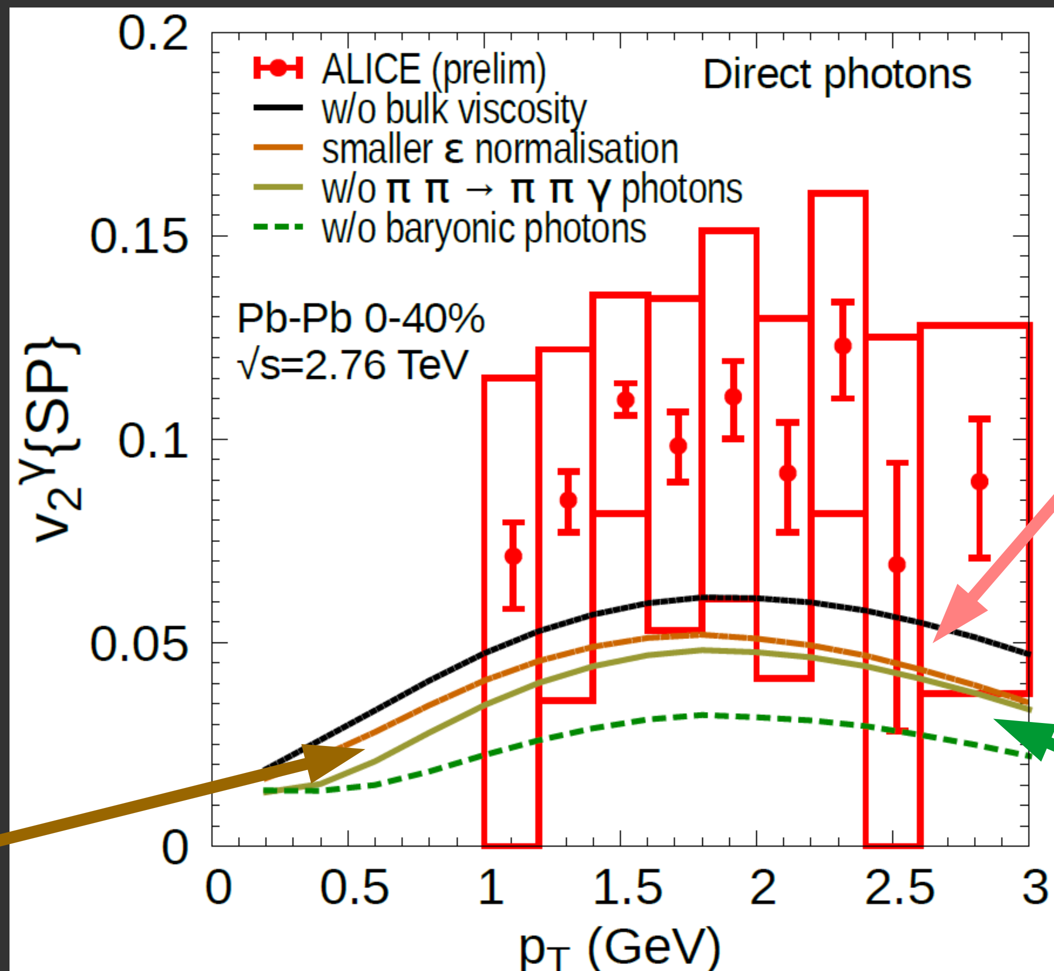
Bulk viscosity allowed for better description of hadronic observables



Solid line: **with bulk viscosity**

Dashed line: **without bulk viscosity (shear only)**

Indirect effect of bulk viscosity & other changes



Change in energy density normalisation due to the introduction of bulk viscosity

Inclusion of photons produced from baryons

Inclusion of photon production through pion bremsstrahlung

Summary

- Bulk viscosity:
  - Good agreement with hadrons
  - Increases low p_T photon v_2, decreases high p_T photon v_2 (change shape of direct photon v_2)
- Comparison with direct photon data:
  - Much reduced tension between calculations and measurements spectra and v_2 (within uncertainties in many p_T bins)
- Comparison with dileptons:
  - Work in progress (w/ G. Vujanovic et al)

Where to go from here?

- Late stage photons produced from transport model?
- Re-evaluation of prompt photons:
  - Inclusion of parton energy loss (fragmentation photons)
  - Photon production through jet-QGP interactions
- Understand theoretical uncertainties on the photon emission rates
  - Systematic comparisons between different thermal rates (for both QGP, cross-over & hadronic phases)?
  - Effect of viscosity on photon emission rates?

Direct photons: where to go from here?

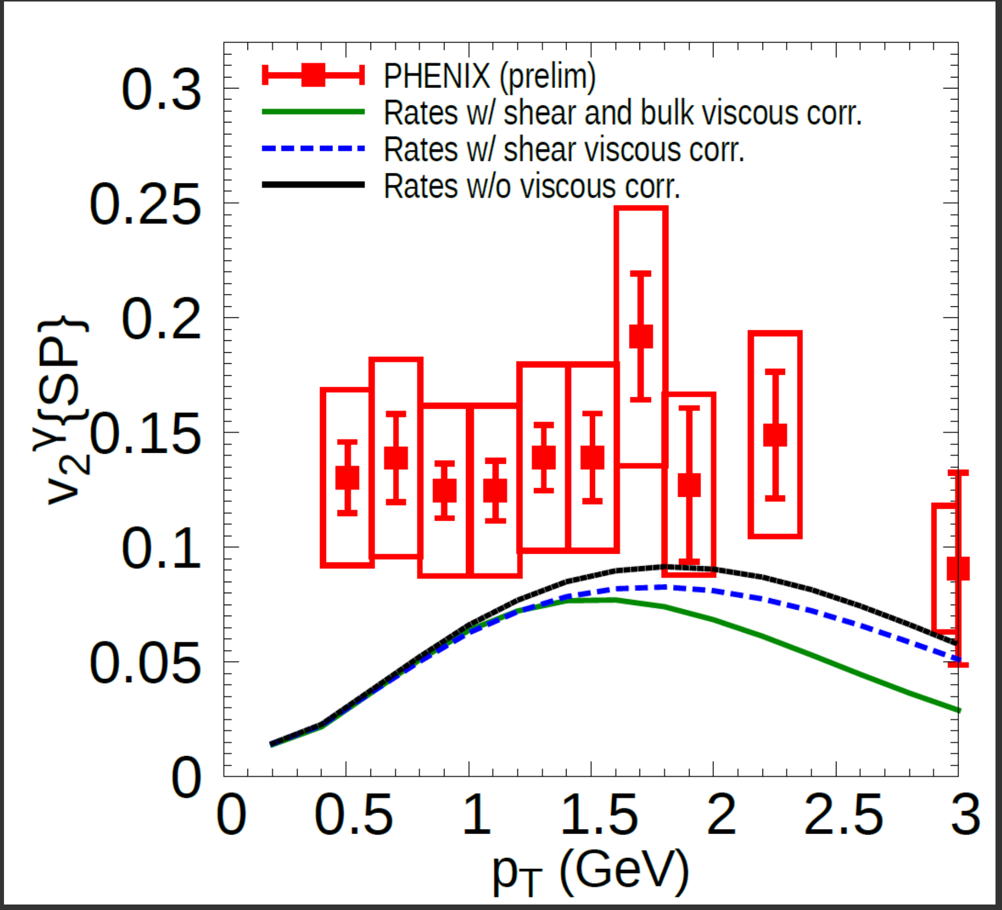
Quantified uncertainties & future directions

(Known knowns, known unknowns & unknown unknows)

Effect of viscosity on rates

Viscous hydrodynamics = Medium is out-of-equilibrium

► Must correct photon emission rates ◄



RHIC

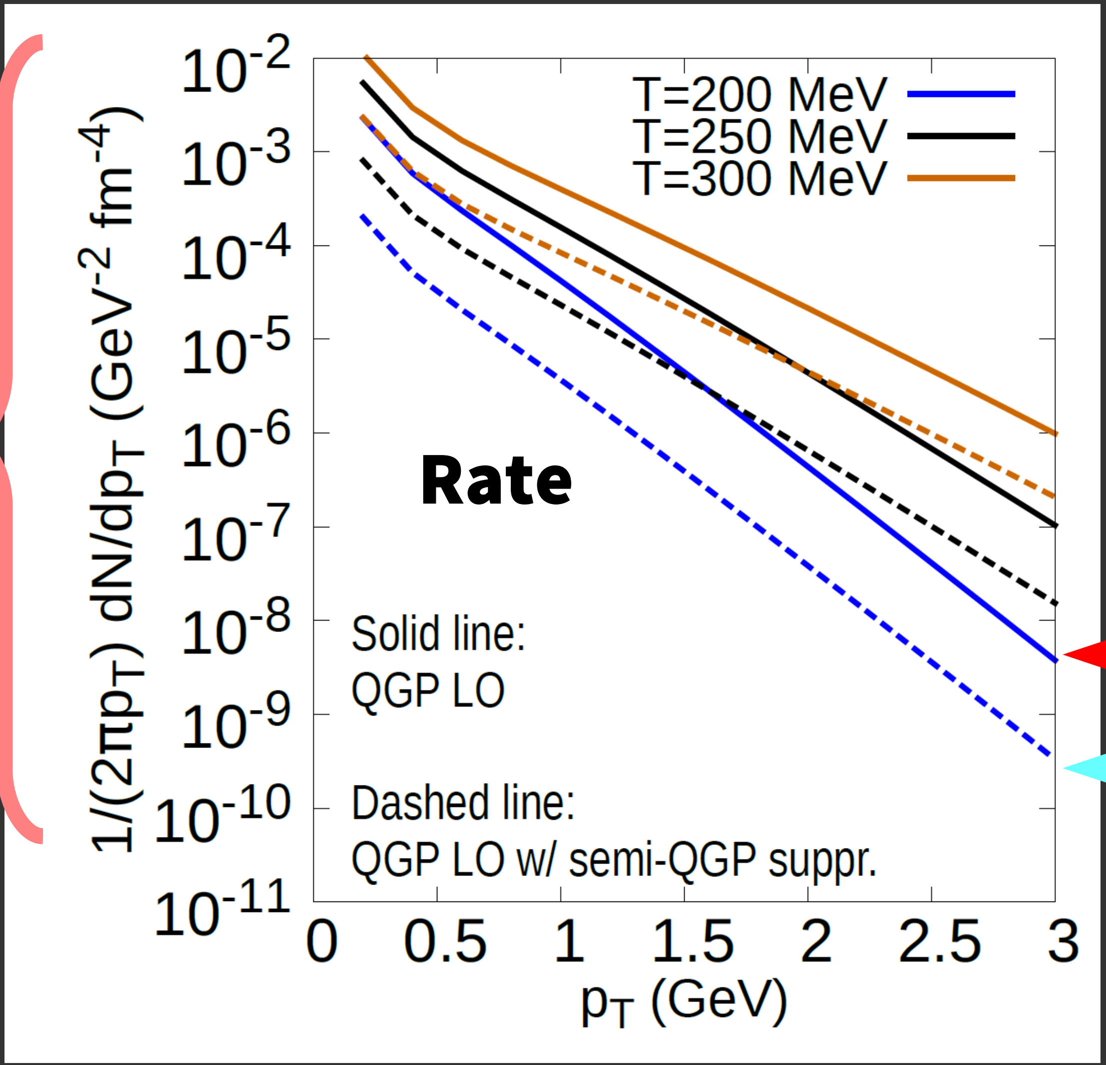
20-40%

Viscous corrections to rate suppress the v_2 at high p_T

Thermal photon rates: QGP

Different thermal photon emission rates

e.g.
QGP
(Arnold, Moore, Yaffe)
vs
semi-QGP
(arXiv:1409.4778)
rates



QGP

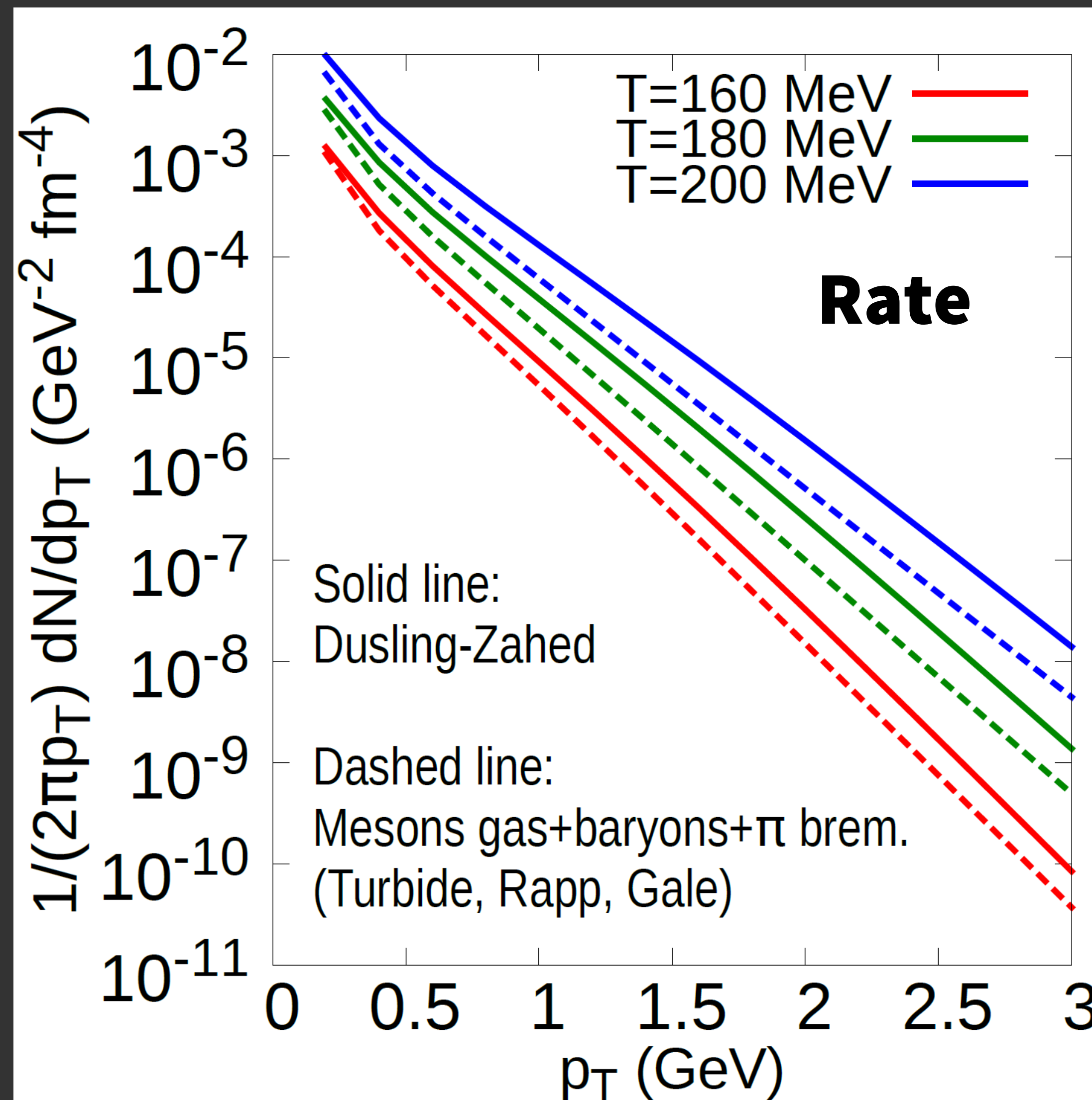
semi
-QGP

c.f. Shu Lin's talk later this morning

Thermal photon rates: hadronic

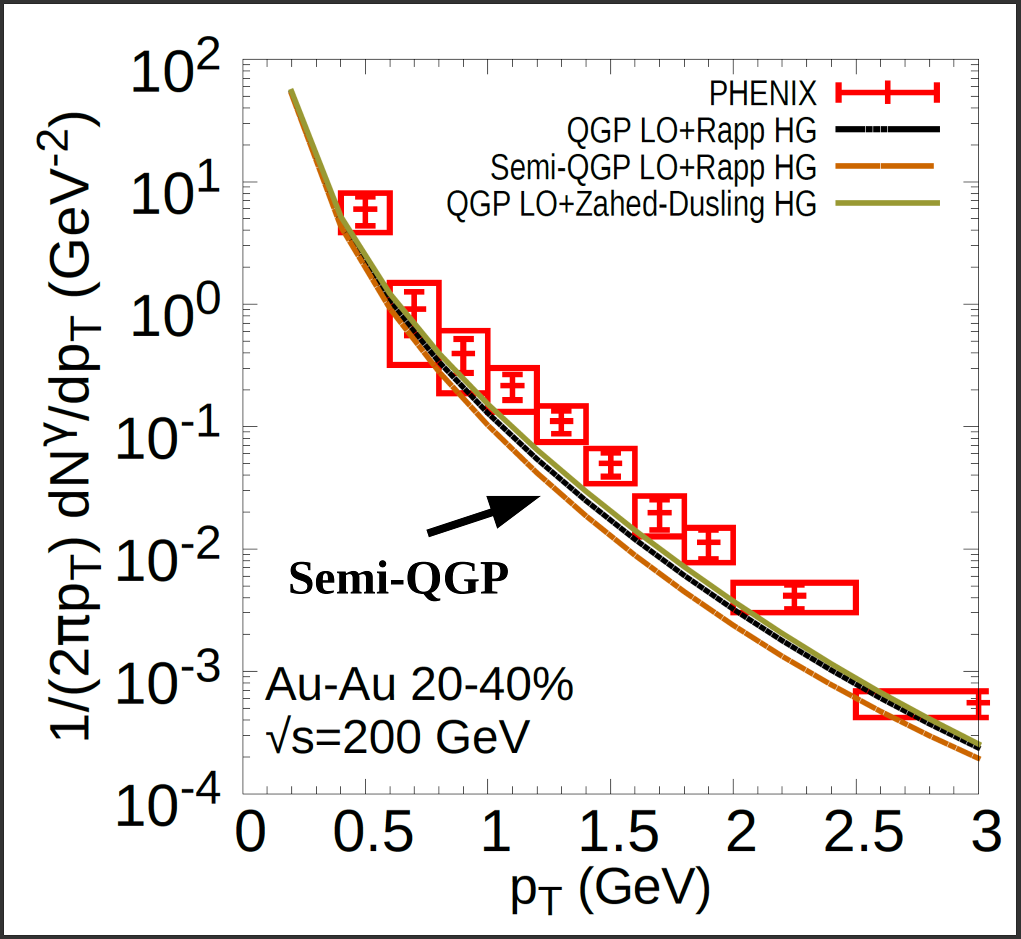
Different thermal photon emission rates

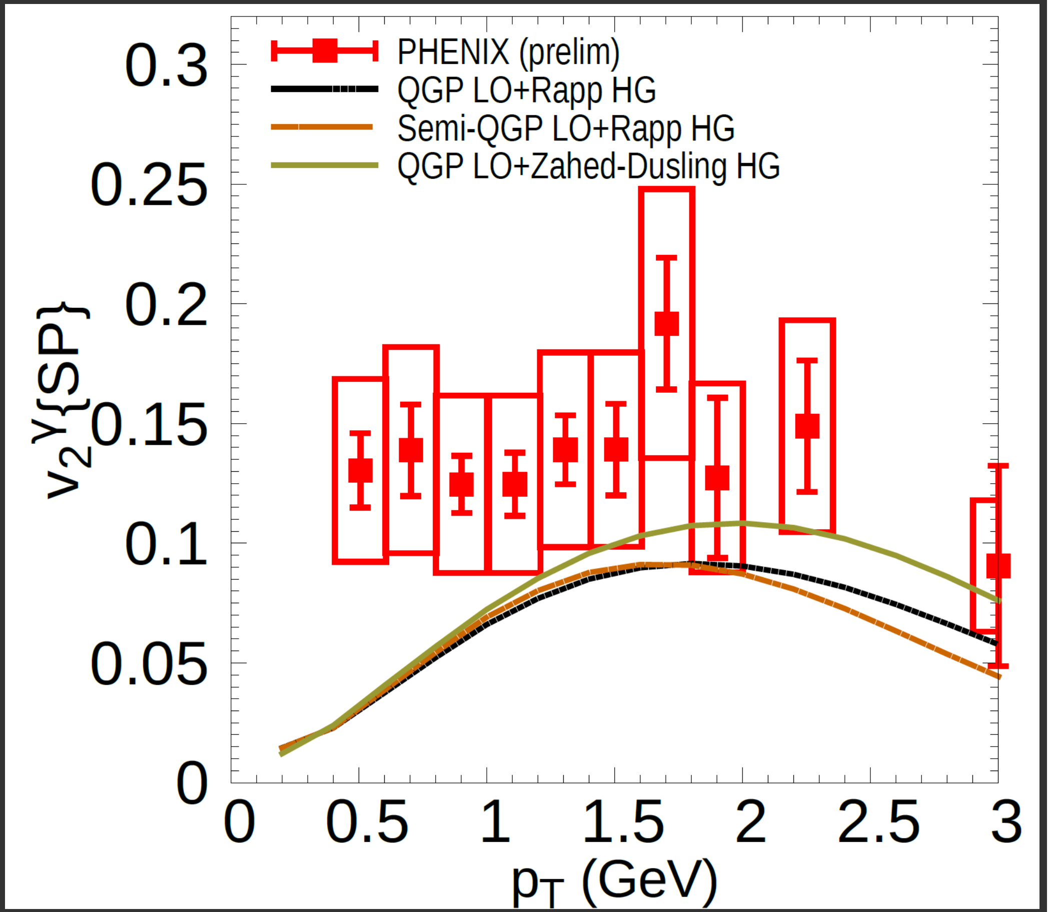
e.g.
Effective Lagrangian +in-medium ρ self-energy (McGill & Texas A&M)
vs
Chiral reduction & density expansion (Dusling & Zahed)



Different emission rates = Different prediction for spectra and v2

RHIC 20-40%





(No viscous corrections to photon rates here)

Thermal rates: Bottom line

Theoretical uncertainties on thermal emission rate

=

uncertainty in calculations

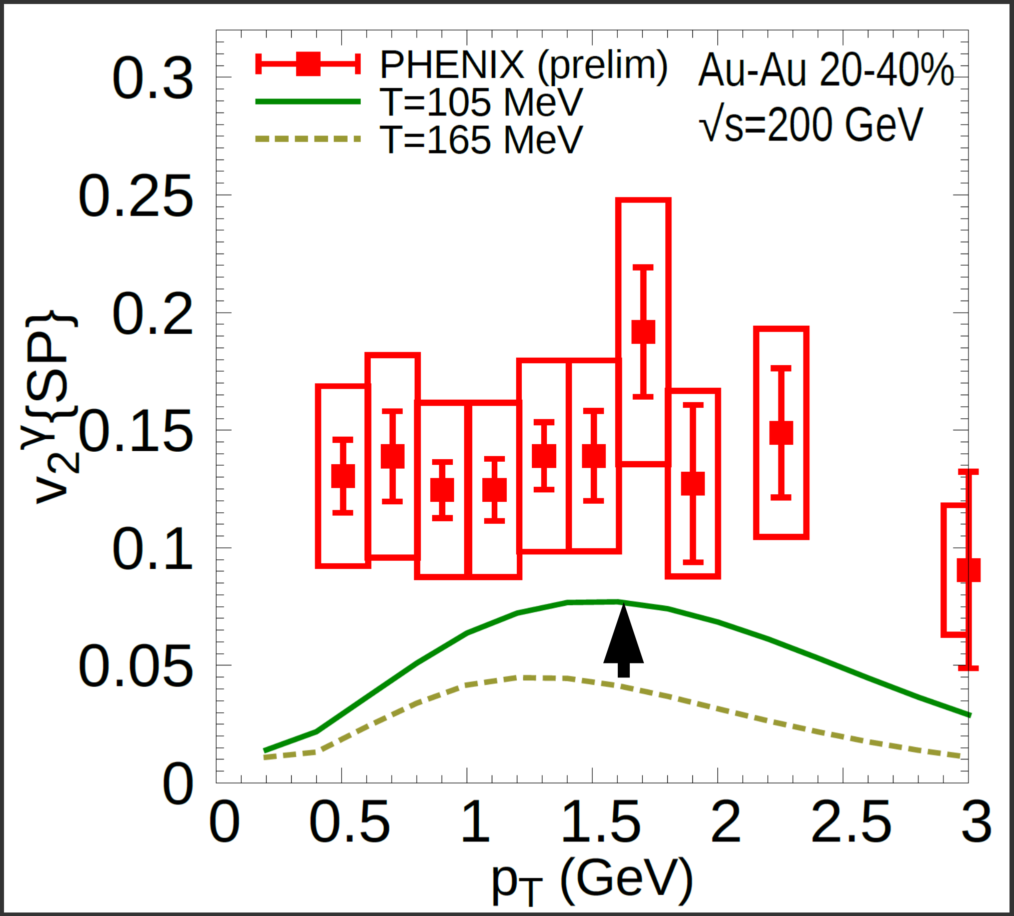
Also: important corrections from viscosity to photon emission rates

Post-freeze-out photons

RHIC 20-40%

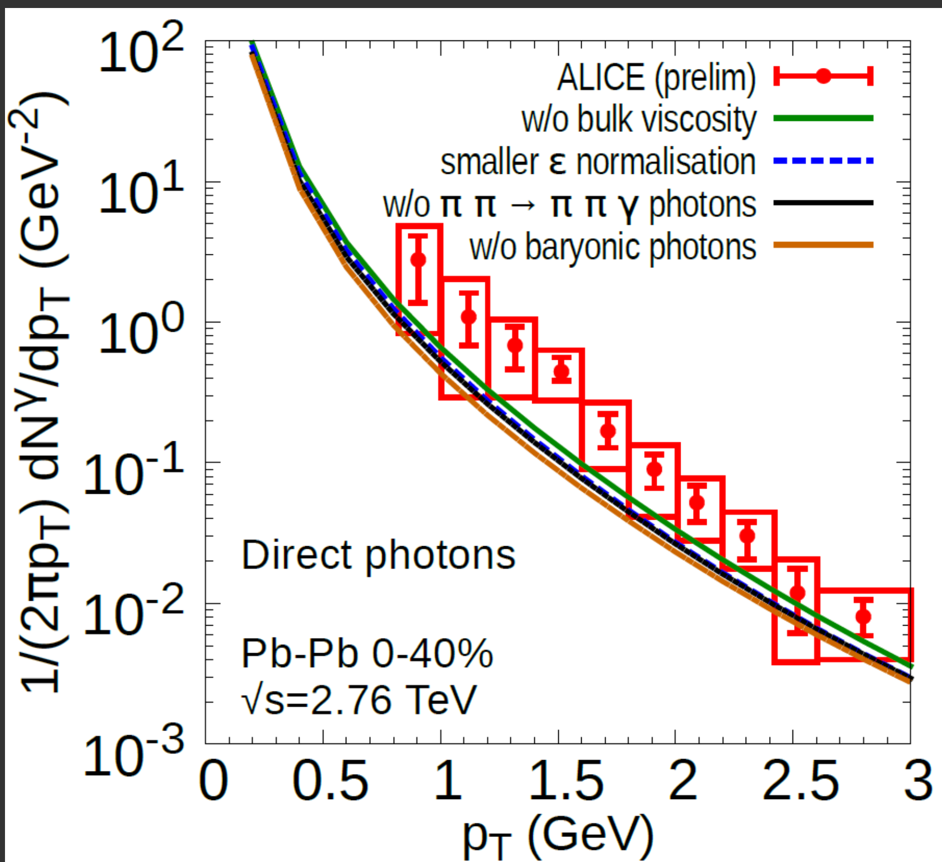
Lots of photons produced at low temperature

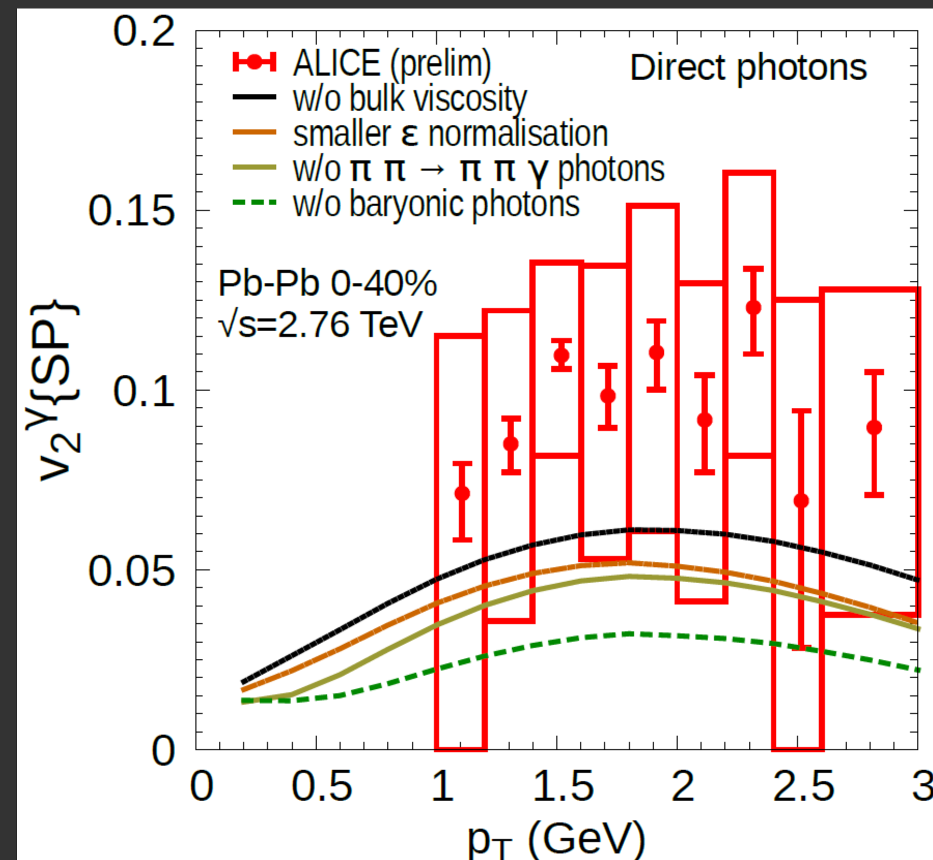
Use afterburner as for hadrons?



Backup

Indirect effect of bulk viscosity & other changes





Second order hydrodynamics

- Hydrodynamics - MUSIC (**τ>0.4 fm/c**)

2+1D second-order relativistic hydrodynamics

$$\partial_\mu T^{\mu\nu}(X) = 0$$

Energy density and pressure related through <u>equation of state</u>

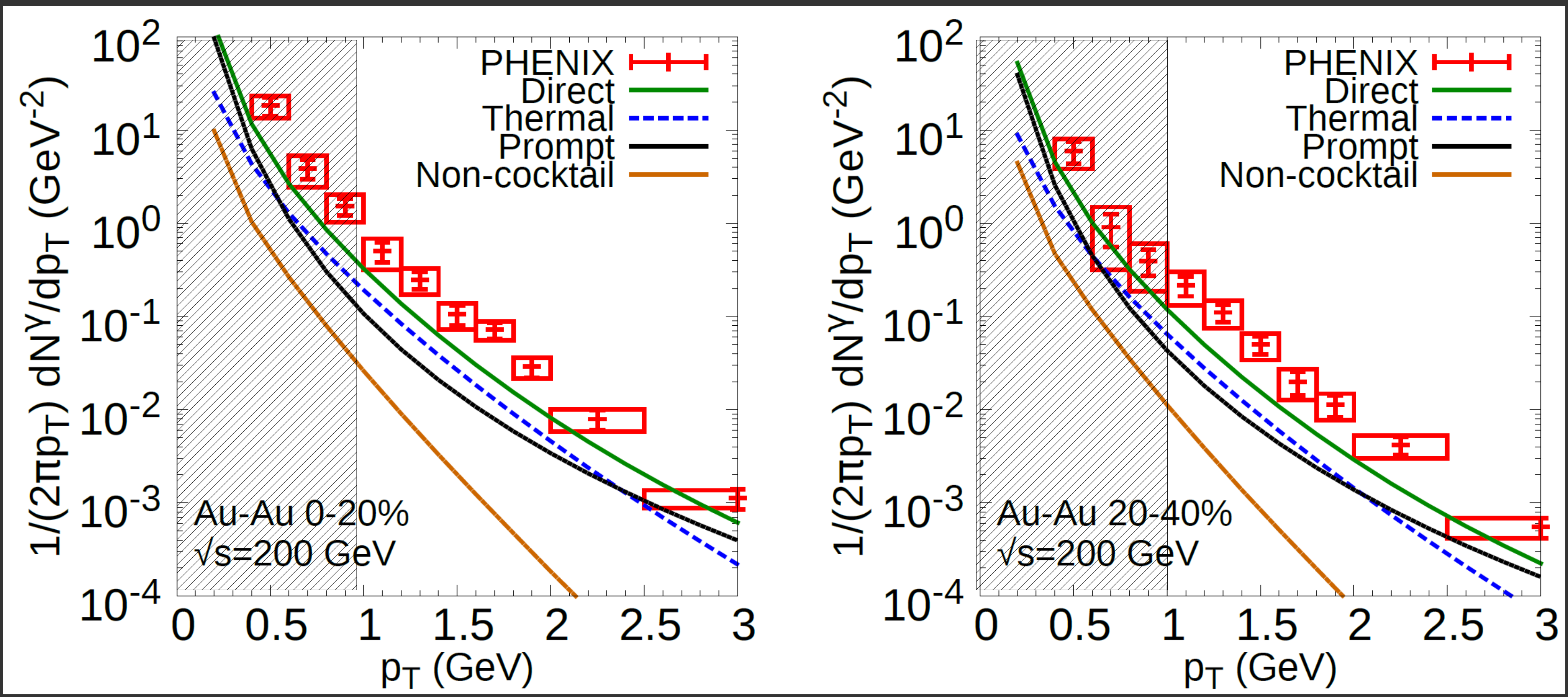
$$T^{\mu\nu}(X) = \epsilon(X)u^\mu(X)u^\nu(X) - [\mathcal{P}(X) + \Pi(X)]\,\Delta^{\mu\nu}(X) + \pi^{\mu\nu}(X)$$

Equation of state from lattice and hadron resonance gas

(Huovinen and Petreczky. 2010)

RHIC $\sqrt{s}_{NN}$=200 GeV: spectra

Direct photon spectra



0-20% **20-40%**

Viscous corrections to photon rates

Thermal photons:

$$E\frac{d^3N}{d\mathbf{k}} = \int d^4X \boxed{E\frac{d^3\Gamma}{d\mathbf{k}}}\left(K^\mu, \boxed{u^\mu(X), T(X), \pi^{\mu\nu}(X), \Pi(X)}\right)$$

"Thermal" photon production rate

Spacetime profile of medium

Modification of thermal photon rates due to shear and bulk viscosities

Example: Meson gas rates

$$k\frac{dR}{d^3k} = N\int \frac{d^3p_1}{2E_1(2\pi)^3}\cdots\frac{d^3p_m}{2E_m(2\pi)^3}\cdots\frac{d^3p_{m+n}}{2E_{m+n}(2\pi)^3}(2\pi)^4\delta^{(4)}\left(\sum_{i=1}^{m}P_i^\mu - \sum_{j=m+1}^{m+n}P_j^\mu - K^\mu\right)$$
$$\times|\mathcal{M}|^2 f_{B/F}(P_1)\cdots f_{B/F}(P_m)(1\pm f_{B/F}(P_{m+1}))\cdots(1\pm f_{B/F}(P_{m+n})),$$

$$f_0(p) \Rightarrow f_0(p) + df_{shear}(p) + df_{bulk}(p)$$

Correcting rates

All thermal rates

Rate	Ideal?	Shear correction?	Bulk correction
QGP $2 \to 2$	Yes	Yes	Partial
QGP bremsstrahlung	Yes	No	No
HG Mesons	Yes	Yes	Yes
HG Baryons	Yes	No	No
HG $\pi + \pi$ bremsstrahlung	Yes	No	No